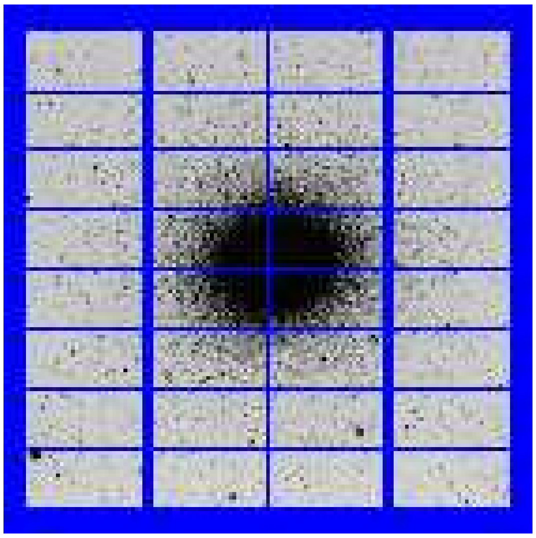

OMEGACAM

User Manual

OmegaCAM Instrument Consortium

Document Number:	VST-MAN-OCM-23100-3110
Issue Number:	1.2
Issue Date:	15.11.2004
Author:	K. Kuijken

Distribution List

Recipient	Institute / Company	No. of Copies
D. Baade	ESO	1

Document Change Record

Issue	Date	Sect. / Paragr. affected	Reasons / Remarks
1.0	31.03.2004	all	first issue (PAE)
1.1	13.05.2004	most	minor changes in response to first RIXes (DBA, RHA)
		3.2	mpe/06 Section on use of ADC added
		2.3	mpe/09
		tab1	dba/03
		2.5–7	dba/05
		3.1.1	dba/06
		3.1.2	dba/07
		3.3.1	dba/08 , tsz/09
		3.3.3	mpe/04
		4	mpe/07
		4.2	rha/01
		app B	dba/10
		app E	dba/09
		app D	dba/11
1.2	15.11.2004	most	general editing of the text, updating of figs (many rix)
		1.3,1.4	New dba/2/01
		2	VST light path figure added fse/2/02
		2.1	Comparison with WFI added
		2.2.1	Rewritten
		2.2.2	Added dba/2/31
		(ex) 2.5-2.7	Reorganized to 2.5 dba/05
		2.7	New fse/2/03
		2.8	New (placeholder for now) fse/2/04
		3.1	Observing modes → Offsetting modes mpe/01, dba/2/15
		3.1.2	Name of observing strategy keyword corrected
		Table 3	Corrected error on jitter data product
		3.2	Error corrected (displacement towards zenith) fse/2/08
		3.4.4	Section on Overheads added fse/2/10
		3.5	Section on reaching background limit added dba/2/24
		3.6.7	Remanence placeholder added
		4.1	Figure added with calibration schedule fse/2/11
		4.2	Point 8: corrected jitter data product
		app B	Figure fixed and updated dba/10
		(ex) app D	→ template manual (improved starext description) dba/11, fse/2/15

Contents

List of Tables

List of Figures

1 Introduction

1.1 Scope

OmegaCAM is the wide-field imager for the Cassegrain focus of the VLT Survey Telescope (VST) on Paranal, a 2.6m modified Richie-Chretien alt-az telescope designed specifically for wide-field imaging. It is the only instrument on this telescope, and is operated most nights. In principle all observations are carried out in service mode. Its main function is to perform large optical imaging surveys, which may be used to feed the VLT telescopes with targets. With its wide field, broad-band filter set, and image quality matched to Paranal seeing conditions, OmegaCAM is well-suited to this task.

This document serves as a user manual for those planning or preparing observations with OmegaCAM. It describes the main instrument characteristics, and how to observe with it using Observation Blocks and Observing Templates.

1.2 More Info

Further information can be obtained by contacting ... `TBD by ESO.`

1.3 References

[**RD1**] Template Manual, VST-MAN-OCM-23100-3111.

[**RD2**] Calibration Plan, VST-PLA-OCM-23100-3090.

[**RD3**] DFS User Requirements, VST-SPE-OCM-23100-3050.

[**RD4**] WFI documentation, see `http://www.ls.eso.org/lasilla/sciops/2p2/E2p2M/WFI/` .

[**RD5**] P2PP instructions, see `http://www.eso.org/observing/p2pp/` .

1.4 Acronyms

ADC: Atmospheric dispersion compensator, a device which corrects for the chromatic effects of the atmosphere at low elevations.

CCD: Charge-couple device, a solid-state, panoramic light detector of high quantum efficiency.

DFS: Data Flow System.

e2v: Manufacturer of the OmegaCAM CCDs.

ETC: Exposure Time Calculator, a software tool provided by ESO as an aid in planning observations.

FWHM: Full Width at Half-Maximum.

MPG: Max Planck Gesellschaft.

OB: Observation Block, a set of instructions to telescope and instrument to carry out a specific observation.

OmegaCAM: The wide-field CCD camera for the VST.

P2PP: Phase 2 Proposal Preparation, the process at ESO in which the users define the OBs for their approved programmes by means of special software.

PA: Position Angle, orientation of the field of view on the sky.

RMS: Root-mean square.

SDSS: Sloan Digital Sky Survey, a large imaging and spectroscopy survey of (mostly) the Northern hemisphere. OmegaCAM's science filter set include the five SDSS filters $u'g'r'i'z'$.

USNO: US Naval Observatory. Their all-sky catalogue is used for astrometric calibration of OmegaCAM data.

VLT: Very Large Telescope, four 8m telescopes on ESO's Paranal Observatory.

VST: VLT Survey Telescope, a 2.6m telescope at ESO's Paranal Observatory dedicated to optical surveys, and host to OmegaCAM.

WFI: Wide-Field Imager, an 8-CCD mosaic camera on the ESO/MPG 2.2 telescope on La Silla with similar pixel scale and sensitivity to OmegaCAM.

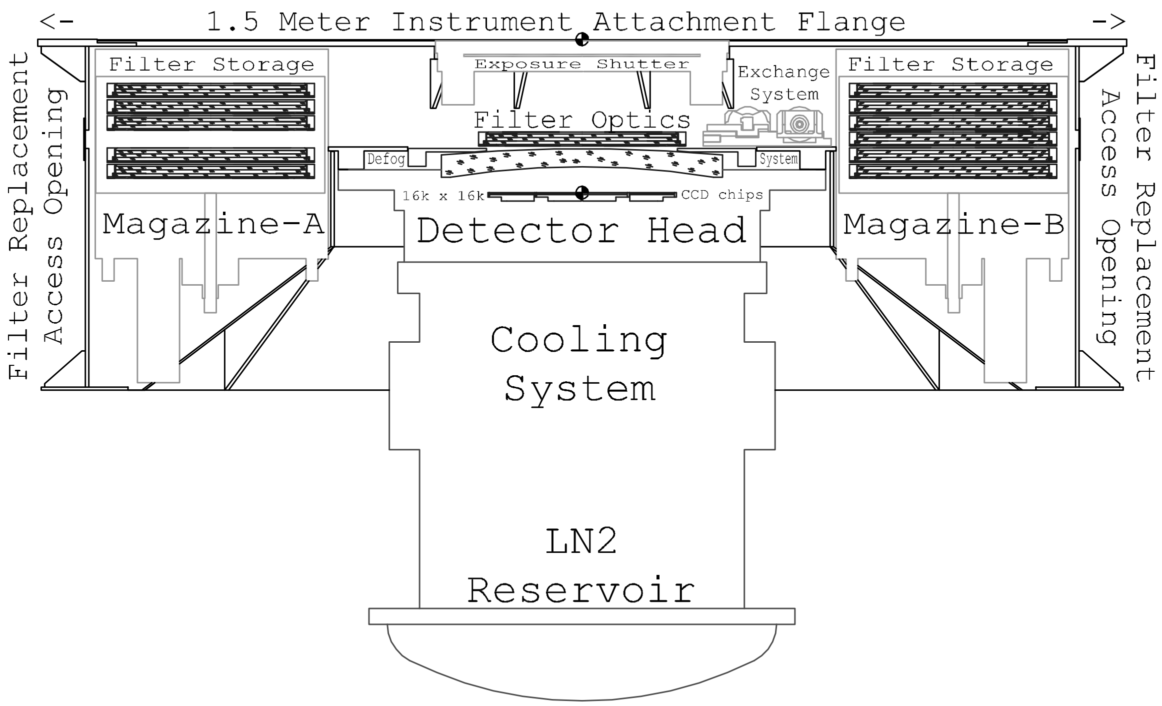

Figure 1: Schematic view of the instrument. Key components are labelled.

2 Instrument characteristics

2.1 Overview

OmegaCAM (see Fig. 1) is the wide-field imager for the Cassegrain focus of the VLT Survey Telescope (VST) on Paranal, a 2.6m modified Richie-Chretien alt-az telescope designed specifically for wide-field imaging. It is the only instrument on this telescope, and is operated most nights. In principle all observations are carried out in service mode.

The VST/OmegaCAM system is designed for good seeing-limited image quality over a wide field. The telescope has an actively controlled meniscus primary mirror, an active secondary, and an image analysis system. It contains two interchangeable correctors: one is a high-throughput two-lens corrector which works in U-Z bands, the other contains an Atmospheric Dispersion Corrector (ADC) for work at lower elevations. The ADC has no throughput in the U band.

The optical layout of the VST is illustrated in Fig. 2.

The VST provides a 1 degree unvignetted field of view, which OmegaCAM samples with a 32-CCD, 16k x 16k detector mosaic (Fig. 4) at 0.21 arcsec per pixel (0.214 for the two-lens corrector, 0.215 for the ADC configuration). The CCDs are thinned, blue-sensitive, 3-edge buttable CCD44-82 devices from e2v of high (but not perfect) cosmetic quality. Image quality is specified such that in the absence of seeing 80% of the energy from a point source should fall within a 2x2 pixel area over the full field (see example spot diagrams in Fig 3). The field distortion is very low, so that the image scale is virtually constant over the whole field. There are narrow gaps between the CCDs: the overall geometric filling factor of the array is 91.4%.

In addition to the 32 CCDs making up the science array, OmegaCAM also contains four auxiliary CCDs around the edges of the field. Two of these are used for autoguiding, so that both field position and rotation can be tracked accurately. The other two auxiliary CCDs are mounted 2mm outside the

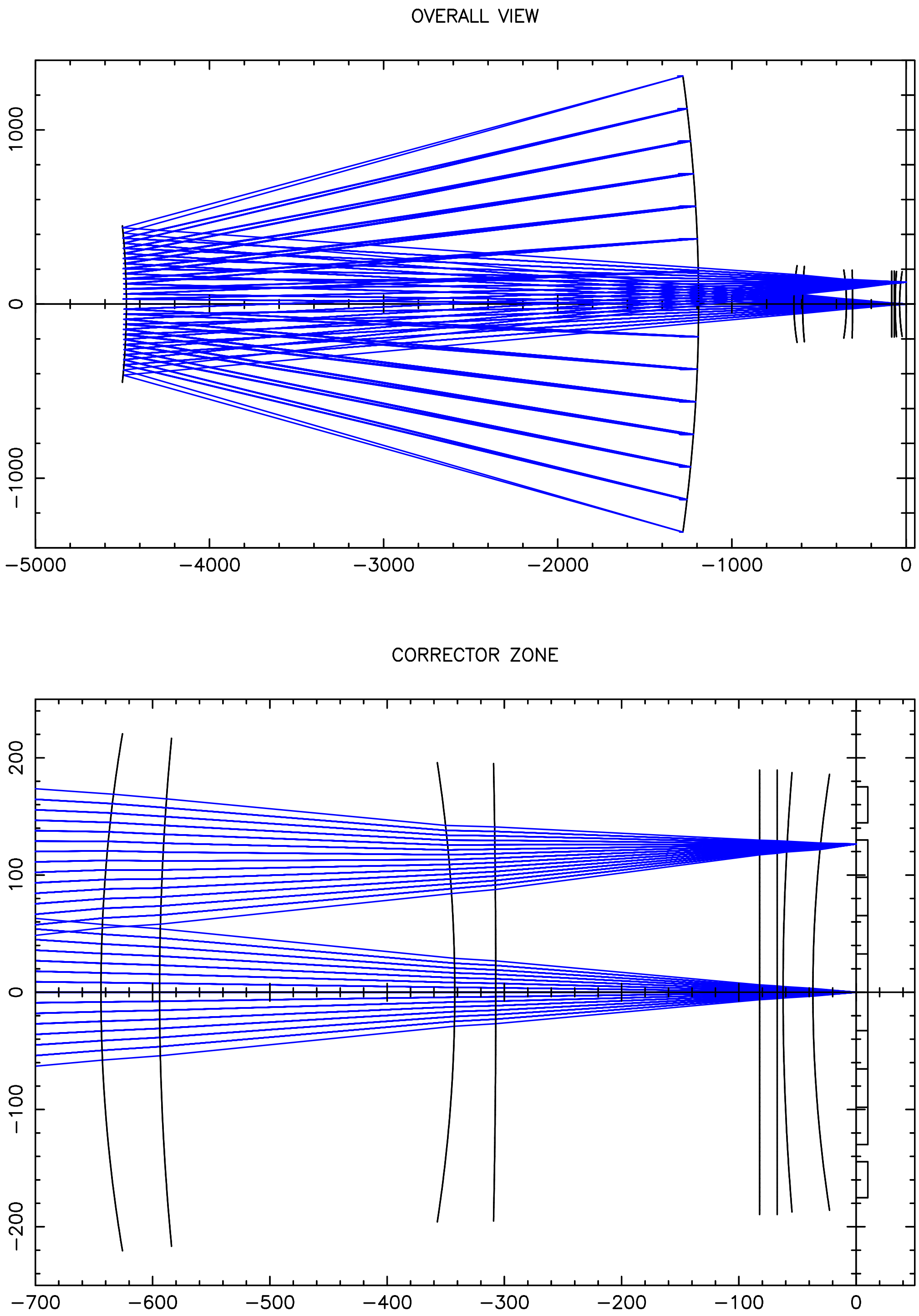

Figure 2: Optical layout and selected light paths through the VST. The configuration with the two-lens corrector is shown. The bottom panel shows a zoom onto the corrector optics: the incoming light passes through two spherical lenses, a planar filter, and the spherical dewar entrance window before striking the CCDs on the right. Scales are in mm.

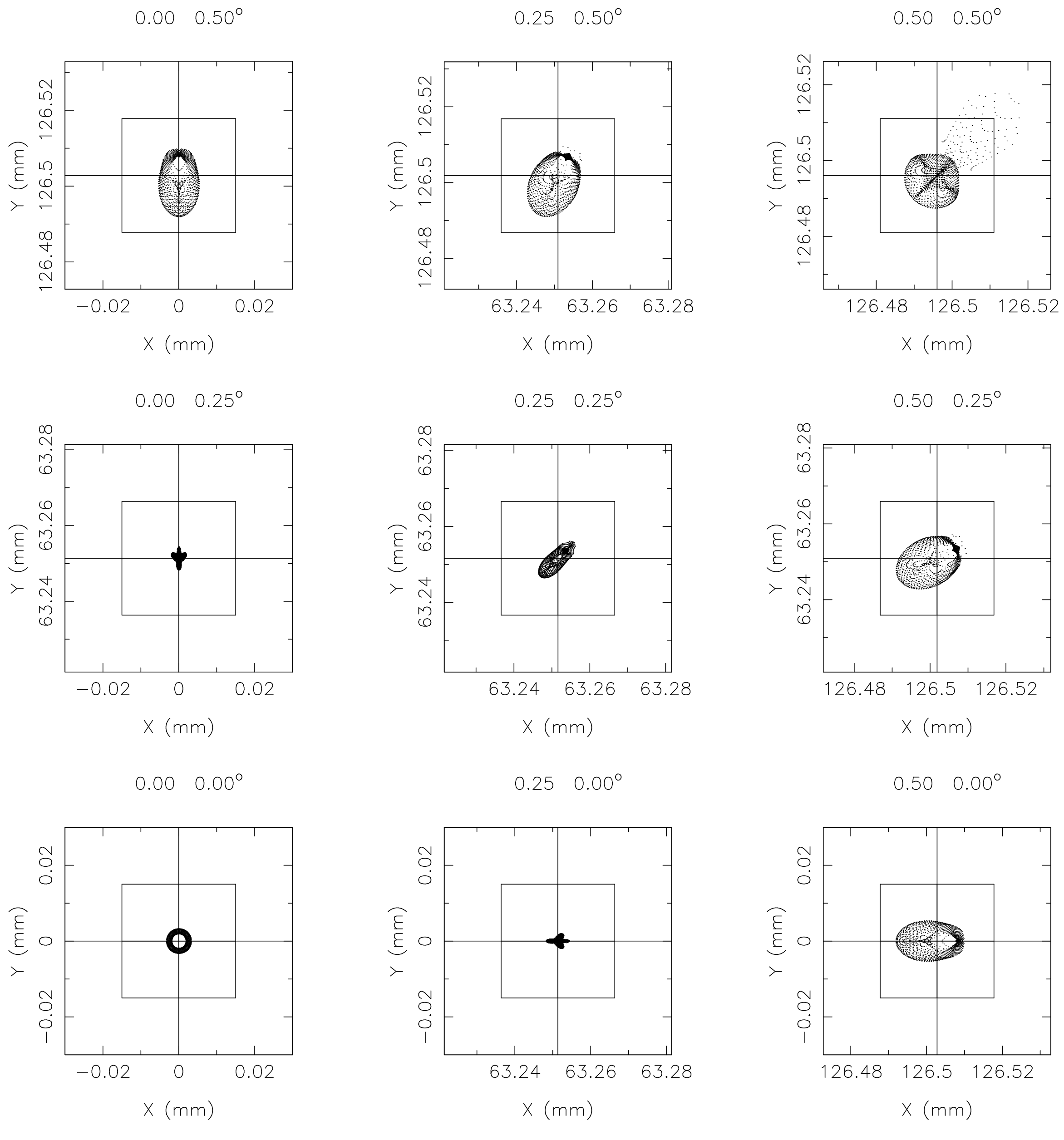

Figure 3: Sample spot diagrams for 500nm light in the OmegaCAM focal plane. A 2x2 pixel grid (30μm $\times$ 30μm, corresponding to $0.43''$) is shown as well.

focal plane (one in front, one behind), and are used for recording defocused star images for on-line analysis of the image quality. The CCD layout in the focal plane is shown in Fig. 4 and in more detail in Appendix B.

OmegaCAM contains a 12-filter exchange mechanism. Currently the available filters include the Sloan $u'g'r'i'z'$ set, Johnson B and V filters, several narrow-band filter mosaics, a Strömgren v filter, and a special calibration filter (see Table 1).

OmegaCAM data are taken in the context of a calibration plan [**RD2**] that ensures that all data can be photometrically and astrometrically calibrated to 0.05 magnitudes and 0.1 arcsec rms precision, respectively.

Compared to the wide-field imager (WFI [**RD4**]) on the ESO/MPG La Silla 2.2m telescope, OmegaCAM on the VST offers

1. a four times larger field
2. better cosmetic quality CCDs
3. a primary mirror of 1.4 times the area
4. year-round operation in service mode
5. better image quality
6. a data flow pipeline for automatic reduction of data
7. the Sloan filter set

2.2 Filters

The filter exchange mechanism (Fig. 5) selects filters from two magazines located either side of the focal plane inside the instrument, and slides these into the beam. Each magazine can store six filters. Filter positioning is repeatable to ca. 1 pixel accuracy.

The available filters are listed in Table 1. Transmission curves as measured in the lab are included in Appendix A.

The filters are sandwiches of glass substrates, ca. 14mm thick. Each filter has a baseplate (usually made of BK7) which provides the mechanical support and mounting to the filter frame. Further layers of glass are glued onto this base plate, and provide the filter bandpass, either through coating or by means of coloured glass. In some cases (the 'segmented' filters) these layers consist of four quadrants, and the interface of the quadrants casts a slight shadow in the form of a cross onto the image plane. The narrow-band filters consist of quadrants where each quadrant has a different bandpass. By offsetting the telescope in half-degree steps, and/or rotating the instrument through multiples of 90 degrees, the full field of view can be exposed in all four bandpasses. The header of the images records which CCD was exposed with which filter segment.

Filter exchange time varies from 50 to 110 seconds, depending on how far the magazines need to move, and on whether the incoming and outgoing filters belong in the same magazine or not.

The Calibration filter is used to observe standard star fields in four bands simulteneously. The result is used to monitor variations in the atmospheric extinction throughout the night, and can be used to deduce atmospheric absorption via an atmospheric extinction curve. For this purpose specially calibrated standard star fields (Landoldt fields, extended to a square degree) have been established around the celestial equator, and near the South celestial pole.

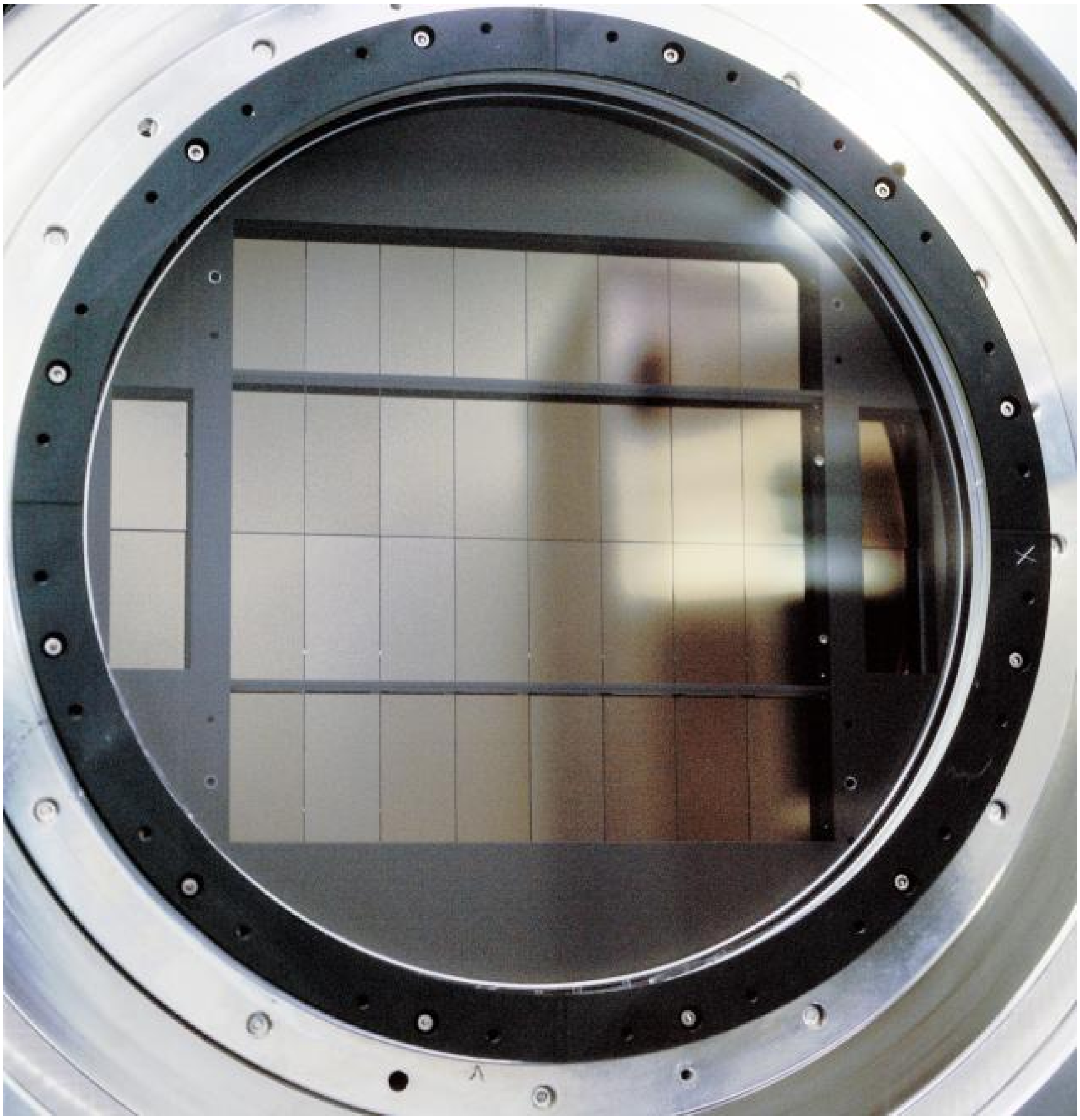

Figure 4: The layout of the 32 science CCDs and the four auxiliary CCDs in the focal plane. The science array covers a 1 degree x 1 degree area of sky, with 16k x 16k pixels of 0.21 arcsec. All CCDs fit inside a circle of diameter 1.4 degrees on the sky.

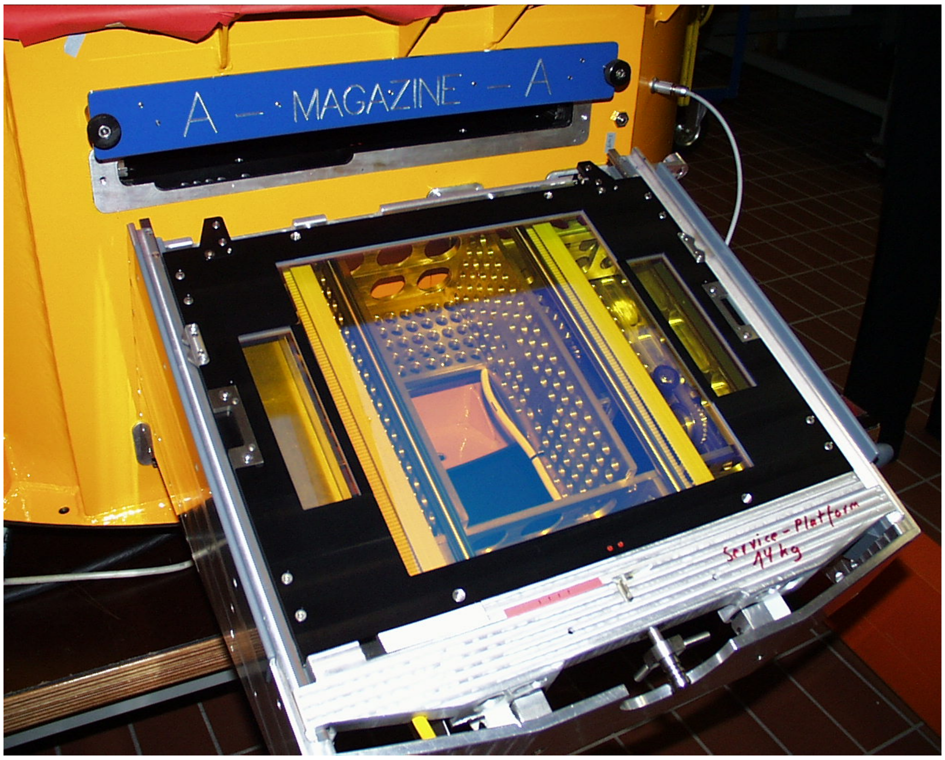

Figure 5: A single OmegaCAM filter ready to be loaded into the instrument. Note the separate filters covering the auxiliary CCDs.

Table 1: Filters available in OmegaCAM `TO BE UPDATED`

Filter name	System	λ (nm)[a]	$\Delta\lambda$ (nm)[b]	P2PP name	comment[c]
u'	SDSS	350	60	u_SDSS	IF, M
g'	SDSS	480	140	g_SDSS	IF, M
r'	SDSS	625	140	r_SDSS	IF, M
i'	SDSS	770	150	i_SDSS	IF, M
z'	SDSS	910	120	z_SDSS	IF, M
B	Johnson	440	100	B_JOHN	CG, S
V	Johnson	550	100	V_JOHN	CG, S
v	Strömgren	411	21	v_STRM	IF, M
$H\alpha$	—	659, 665, 672, 679	10	H_ALPHA	IF, 4Q
$z = 0.3\ H\alpha$[e]	—	852, 861, 869, 878	13	NB_852_861_869_878	IF, 4Q
Calib[d]	SDSS	u',g',r',i'		u_g_r_i_SDSS	CG, 4Q

[a]Central wavelength and [b]FWHM of filter throughput × mean CCD qe curve; [c]IF=Interference Filter; CG=Coloured Glass filter; M=Monolithic; S=Segmented; 4Q=4 quadrants with different passband. [d]Because of the different manufacturing processes, the Calib filter bandpasses differ in detail from the monolithic filters. [e]This is a private filter for use by Munich University Observatory for the first five years of OmegaCAM operations.

For the filters consisting of different quadrants, the layout of the quadrants on the sky is as follows (for the default orientation of the instrument with PA=0, North is up, East to the left):

Calib: $\begin{array}{|c|c|}\hline u' & g' \\ \hline r' & i' \\ \hline\end{array}$; $H\alpha$: $\begin{array}{|c|c|}\hline 657 & 661 \\ \hline 668 & 679 \\ \hline\end{array}$; $z = 0.3\ H\alpha$: $\begin{array}{|c|c|}\hline 852 & 861 \\ \hline 869 & 878 \\ \hline\end{array}$.

`Dummy configurations to be finalized once filters are available.`

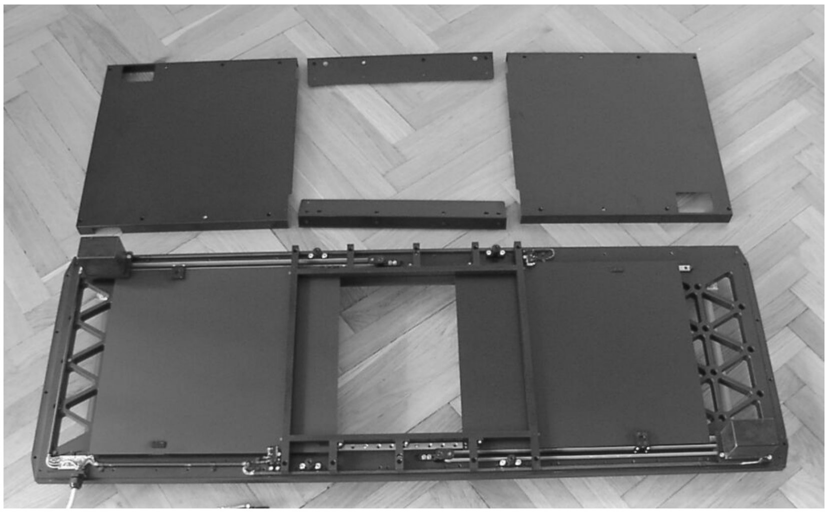

Figure 6: Picture of the partly disassembled shutter unit. The two blades, as well as the central aperture, are visible in the lower part of the unit.

2.2.1 Note on filter magazines

Because the filter frames can only mate with the filter insertion mechanism on one side, the orientation of a filter with respect to the CCD mosaic depends on the magazine in which it was stored. During observations the filter exchange mechanism always returns a filter to the magazine (and slot within that magazine) it came from. However, it may happen that a filter is moved manually from one magazine to the other during daytime operations. This flips the orientation of the filter by 180 degrees.

Manual filter manipulations should always be followed by the taking of a new set of flat fields, but if for some reason old flats need to be used it is important to check that these were taken with the same filter orientation. Which magazine a filter was loaded from is logged in the image headers (keyword INS.FILT1.NO: magazine 'A' contains filter positions 1–6; magazine 'B' positions 7–12).

2.2.2 Providing Private Filters

It is possible, but not simple, to use private filters with OmegaCAM. There are a number of constraints:

1. The filters need to be mounted in special frames. These frames grab the filters by the baseplate, which needs to be approx. 5mm thick. Spare frames exist.
2. Overall optical thickness should be equivalent to 15mm fused silica.
3. The costs of these large filters are high (50-100 kEuro), and manufacturing times long (up to a year or more).

People interested in using private filters with OmegaCAM should contact the ESO User Support Group (`usghelp@eso.org`).

2.3 Shutter

The shutter of OmegaCAM is located on top of the instrument, in front of the filters. It is a low-acceleration, twin-blade photometric shutter of aperture 370×292mm. The leading blade exposes the CCDs, the trailing blade covers them again. By ensuring that both blades travel with the same acceleration profile the exposure is kept homogeneous over the full beam. For very short exposures (below 0.8 s) the trailing blade starts its motion before the leading blade has finished moving. Over the CCDs the blades move at constant speed.

Even for exposures as short as 0.1 seconds, the homogeneity over the field is better than 1%. However, it is important to realize that exposures are not simultaneous: there is a lag of about 0.5 second between the exposures at the leading and trailing edge of the field. For high timing accuracy observations, the delay time

$$t_{\mathrm{delay}} = 0.39 + 0.00174X \text{ seconds} \tag{1}$$

needs to be added to the absolute time of the exposure start and end. Here, X is in mm with respect to the center of the detector mosaic (1mm=14.3 arcsec), and runs along the short sides of the CCDs in the direction of motion of the blades.

The image headers record when each blade started and stopped its motion and hence contain the direction of motion of the shutter.

Note that the shutter blades are quite far from focus: at the shutter location the light from a given star is smeared out over a width of about one tenth of the full shutter aperture. This means that the time over which a given pixel receives photons is longer than the actual exposure time, by an amount of roughly 0.08 s. Seen from an individual pixel the photon rate over time does not have steep edges but is smeared out.

2.4 Detector Mosaic

2.4.1 The 268-Million Pixel Science Array

`TBD with significant ODT input:` Overall cosmetics, QE, linearity, read noise, readout time, gaps between CCDs, position of readout ports, pre- and overscan pixels, brief description of unit detectors, CTE, cross-talk, signal remanence, dark current, windowing, binning, orientation in the sky (when rotator offset angle = 0)

The average throughput of the telescope/correctors/detector chain is shown in Fig. 7. A montage of the QE curves of all CCDs in the mosaic is given in Appendix B.

2.4.2 Auxiliary CCDs

In the periphery of the focal plane OmegaCAM contains four auxiliary CCDs. Two of these are used for guiding, both in position and position angle of the field. The other two are mounted out of focus (one is 2mm in front of the focal plane, one 2mm behind). Analysis of pairs of defocused images from these CCDs allows optical aberrations (defocus, coma, astigmatism, ...) to be measured.

2.5 Auto-Guiding and Focussing

Both the VST and OmegaCAM contain systems for auto-guiding and for focussing. Focussing happens automatically through real-time sensing of the wavefront. Traditional through-focus sequences are only needed to calibrate these auto-focus systems.

2.5.1 VST Guide Probe

The VST contains a guide probe with a pick-off mirror, which can patrol the field in front of the filters. It can be used for guiding the telescope and for its active optics system. When required, the

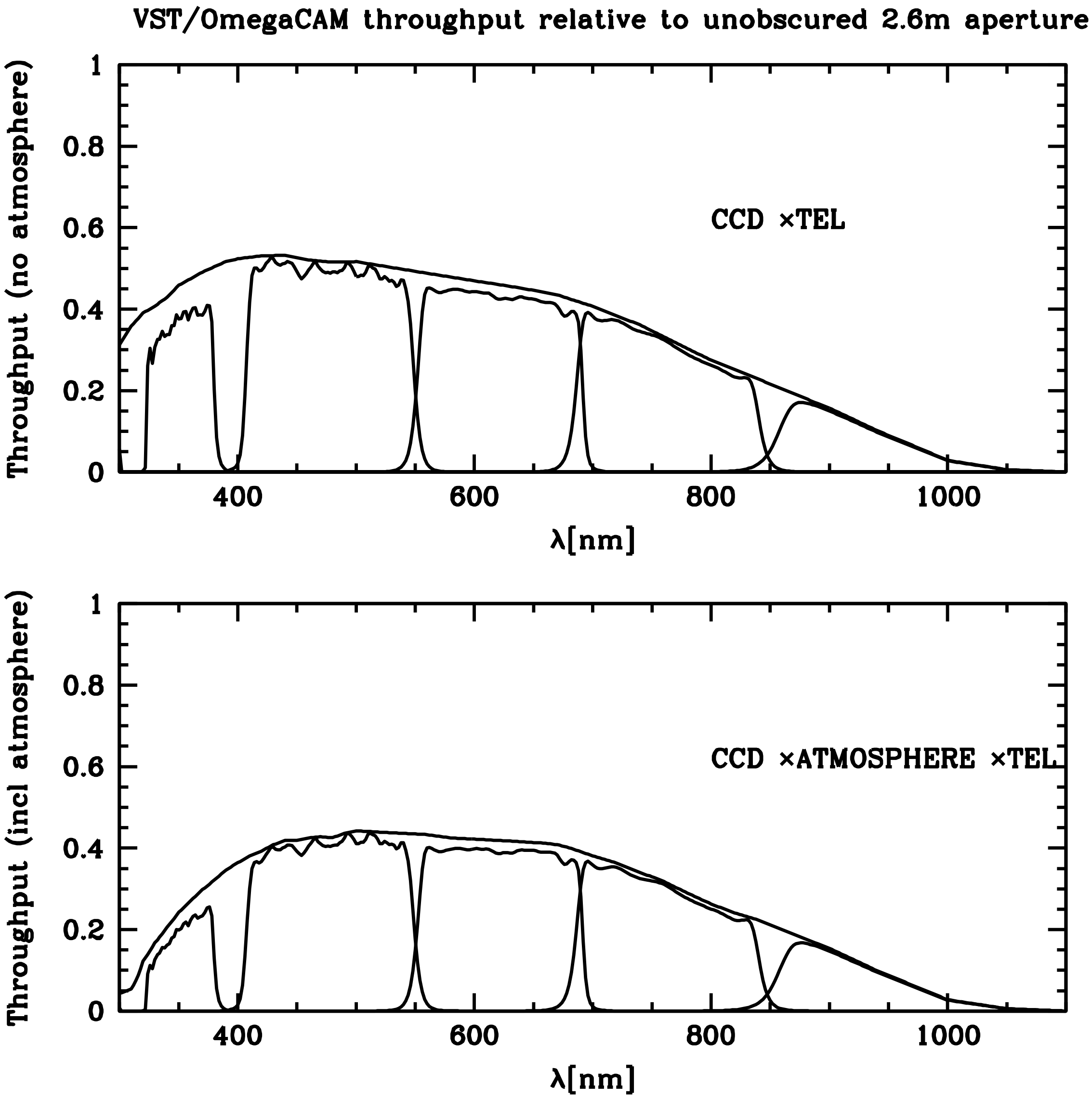

Figure 7: Throughput of the VST / OmegaCAM / CCDs, excluding and including atmospheric absorption (airmass zero and one). The sensitivity of the system including the five Sloan filters is also shown. `To be updated with real measurements.`

probe can be used in between scientific exposures to measure the optical image quality by means of a Shack-Hartmann analysis. This information can then be used to configure the telescope's active optics system.

The probe can also be used for autoguiding and image analysis during scientific exposures. However, unless a suitable guide star exists very close to the edge of the field, the probe vignets the field of view. Use of the OmegaCAM guide sensors is thus to be preferred. Currently, only in case of differential guiding (solarsystem mode) can the VST guide probe be used during a scientific exposure.

2.5.2 Auto-guiding with OmegaCAM

Two guider CCDs are mounted diametrically opposite to each other, near the edges of the field (see Fig. 4). Auto-guiding is done simultaneously on two stars, one on each guider CCDs. This allows field center and rotation to be tracked during an exposure. When the shutter closes, the guider CCDs are not exposed to the sky, and guiding cannot take place. Acquisition of the two guide stars, one per CCD, happens automatically. If after a readout a second exposure is taken of the same field (perhaps with an offset), the guide stars are re-acquired once the shutter is reopened, and auto-guiding attempts to keep the stars on the pixels where they are found.

2.5.3 Image Analysis with OmegaCAM

The other two auxiliary CCDs are mounted out of focus. They intersect the stellar light beams in two planes, one in front of, and one behind, the focal plane. This gives information on the deviation of the beams from perfect cones with apex in the focal plane. Different kinds of aberration result in different shapes for these defocused stars, and this can be used to calculate corrections to be applied to the VST's active primary and secondary mirrors. Acquisition of the two image analysis stars, one per CCD, happens automatically, as does the computation of aberration coefficients.

2.6 Calibration lamps

Dome flat exposures can be taken with calibration lamps mounted at 90° intervals on the top ring of the telescope, illuminating a white screen on the inside of the telescope dome. The lamps are operated by carefully controlling the electric current, and their brightness is stable to about a percent over a timescale of several months.

Dome flat fields are used for monitoring the small-scale (pixel-to-pixel) variations in sensitivity of OmegaCAM, and for overall system throughput monitoring. Two sets of four lamps each are mounted side by side. One set is used for routine daily calibrations, meanwhile the second set is cross-calibrated against the first at regular intervals. Once the lifetime of the first set of lamps has expired, its role is taken over by the second set, and the first set is replaced with new lamps. This procedure ensures a continuous record of throughput measurements, provides dome flat fields, and serves as a daytime health check.

2.7 Photometric Properties

Indicative magnitude zero points (the AB magnitude of a star that generates one electron per second) are given in Table 2.

Because of the way they are constructed, the OmegaCAM filters show some bandpass variation across the field. This variation is mostly axisymmetric, and it introduces a radially dependent colour term. The coefficients of this term are included in the Table.

Filter	Mag zero pt (AB)
u'	24.9
g'	26.4
r'	26.1
i'	25.6
z'	24.3

Table 2: Magnitude zero points for the SDSS filter set. `To be updated, and color terms to be added including modelling of radial variations.`

2.8 Astrometric Properties

`To be added after Comm: accuracy, field deviation, thermal variations(?), header keywords, plot of residuals.`

3 Observing with OmegaCAM

To carry out observations with OmegaCAM, users need to prepare Observing Blocks (OBs) before the observations and submit those to ESO, using the Phase 2 Proposal Preparation (P2PP) system. More details on how to define OBs are given in §3.3. First the offsetting modes, and the effects of atmospheric refraction and dispersion, are described.

3.1 Offsetting Modes and Observing Strategies

3.1.1 Offsetting Modes

OmegaCAM observations can be taken with a number of *Offsetting Modes*: STARE, DITHER, JITTER, or SOLARSYSTEM. They differ in the kind of offsets that are used between exposures, and in the final data product.

1. STARE: A sequence of N exposures of exactly the same part of the sky. No offsets are done. The data product of a STARE observation is a set of 32 stacks of N astrometrically and photometrically calibrated images (one stack per CCD), regridded to a sky coordinate grid. To allow removal of cosmic rays by taking the median of images N must be at least 3.
2. DITHER: A sequence of N exposures with offsets that are sufficiently large to bridge the gaps (up to 80 arcsec) between the CCDs in the detector mosaic. A DITHER observation results in an image which covers the field continuously, without large holes (provided $N > 3$). Some parts of the sky are seen by several CCDs, and all parts of the field are seen in at least $N - 2$ exposures.
3. JITTER: A sequence of N exposures with offsets that are sufficiently large (of order 1 arcsec) to shift cosmetic CCD blemishes to different parts of the sky. A JITTER observation results in a 32-fragment image (one fragment per CCD) in which the gaps between CCDs remain, but in which any part of the sky is seen by at most one CCD.
4. SOLARSYSTEM: A sequence of N exposures in which the telescope is tracked at non-sidereal rates, in order to follow a high proper motion object such as a comet. If required, autoguiding is possible in this mode, using the VST guide probe (which may slightly vignet the field).

The pattern of offsets between successive exposures on a field distinguishes *dither* and *jitter*. They represent different trade-offs between trying to obtain data with uniform exposure level over the full OmegaCAM field, and trying to avoid having areas on the sky where data from different CCDs need to be combined. Such overlaps can give rise to discontinuities in the way the PSF varies across the field in the final stacked image, but this is unavoidable if the full field is to be exposed.

The key differences between the two modes are summarised in Table 3.

A number of patterns has been pre-defined for dither and jitter. They are described in more detail in the Template Manual [**RD1**].

	JITTER	**DITHER**
Correct what?	CCD blemishes	gaps in focal plane
Offsets	few arcsec	25-100 arcsec
Data product	fragmented 1-square-degree-image	filled 1-square-degree image
Advantage	least fragmented context map	homogeneous exposure level
Penalty	gaps between CCDs	possible sharp changes in PSF

Table 3: Key difference between the dither and jitter modes.

Programmes that require very accurate PSF measurements should preferably use *jitter* as it results in a PSF which varies continuously over each CCD (except near the very edges). *Dither* data should be used if the primary aim is to image a field completely.

3.1.2 Observing Strategies

Observations are also taken under different *Observing Strategies*. Strategies are not implemented in ESO's Data Flow System at the present, but may help the users in their own data reduction. The strategy used is written to the image headers (keyword TPL OBSSTRG).

Strategies extend beyond single OBs. The defined strategies are STANDARD, FREQ, DEEP, or MOSAIC. They can relate to how fields are laid out during observation preparation, and they can also provide specific instructions for data reduction, and for scheduling.

1. STANDARD: Used for a stand-alone OB, with no particular relation to other observations.
2. DEEP: Observations intended to generate a deep image, built up over several (typically many) OBs.
3. FREQ: Observations in which a field is monitored to form a time series. Specific time intervals (from minutes to months) may be specified for such observations as part of P2PP. Specific time intervals can be specified for each OB; more complex scheduling constraints (e.g., "leave at least 2 nights between successive observations") need to be given in the README file submitted together with the OB.
4. MOSAIC: Observations which will be used to map an area of the sky consisting of several (typically many) adjacent pointings.

3.2 Atmospheric Refraction and Dispersion

The atmosphere refracts light, as a result of which sources appear slightly closer to the zenith than they would be without the atmosphere. The effect is slightly wavelength dependent. This has two consequences: *atmospheric refraction* and *atmospheric dispersion*.

3.2.1 Atmospheric Refraction

A star's extra displacement r towards the zenith due to atmospheric refraction is given by

$$r = R \tan z \quad \text{rad} \tag{2}$$

where z is the zenith distance of the star, and R is the refractive index of air minus 1. To a good approximation

$$R \simeq 1\text{arcmin}. \tag{3}$$

(R is slightly wavelength-dependent: see §3.2.2.)

Over the field of OmegaCAM, r takes slightly different values: from the center to the edge z differs by $\delta z = 0.5°$, and so r varies by

$$\delta r \simeq R \sec^2 z \, \delta z \simeq 0.5'' \sec^2 z. \tag{4}$$

Thus, the size of the field changes with zenith distance by an amount $2\delta r \simeq 1.0'' \sec^2 z$. This is not a concern since the astrometric standard stars in the field suffer the same refraction, and so this effect is taken out in standard data reduction.

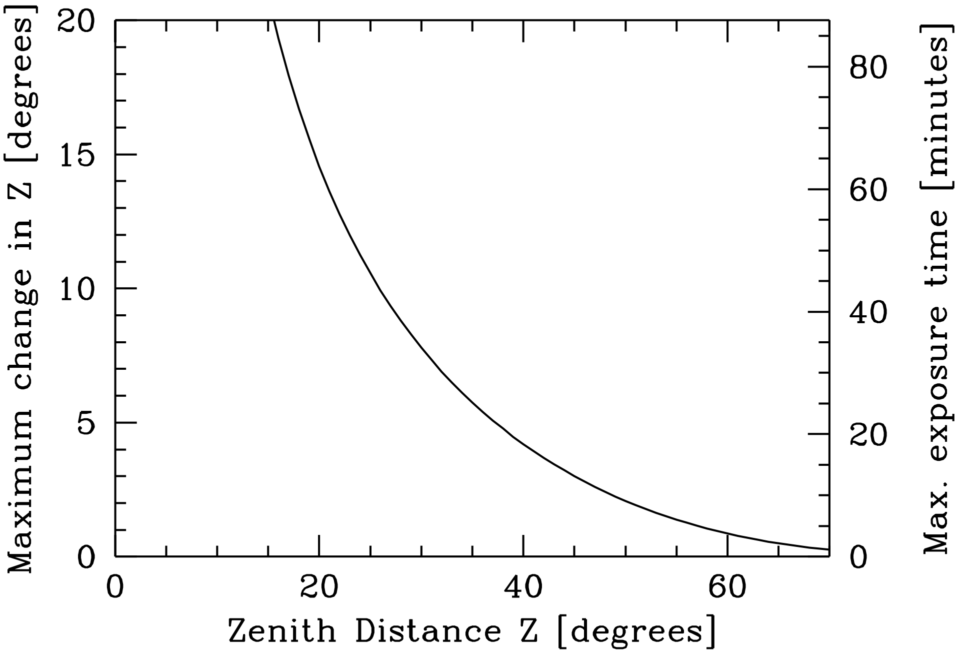

Figure 8: The maximum change ΔZ in zenith distance (degrees) that is allowed during an exposure before the image quality is degraded by 0.1 arcsec due to atmospheric refraction. The right-hand axis approximately translates this limit into an exposure time T (minutes) for a field on the equator, as seen from the Paranal latitude of $-24°$: $T = 4\Delta Z/\cos(-24°)$.

However, atmospheric refraction does affect long exposures at lower elevations. If δr changes significantly during an exposure then it becomes impossible to track objects in the center and outer parts of the mosaic at the same time. As a result, image quality in the outer parts of the field will be degraded. The way to prevent this is to keep the exposures short, and so avoid a large change of δr during an exposure.

For δr not to change by more than 0.1 arcsec over an exposure requires

$$\delta(0.5'' \sec^2 z) < 0.1'' \qquad \text{or} \qquad \delta z < 6° \cot z \cos^2 z. \tag{5}$$

At $z = 45°$, therefore, z must not change by more than 3 degrees per exposure (for a target near the celestial equator this means no more than 12 min exposure); at $z = 60°$ the limit is below a degree change allowed (4 min exposure).

In poor seeing, or if image quality constraints are not so stringent, this limit can be relaxed and presents no practical concern.

Figure 8 shows a plot of the limit given by eq. 5.

3.2.2 Atmospheric Dispersion

Because refraction is wavelength dependent (more strongly so in blue light), the atmosphere turns objects into little spectra with the blue end pointed at zenith. Within the bandpass of a broad band filter this can cause significant image elongation and degradation. To compensate this effect, the VST

Filter	Airmass at which dispersion reaches 0.2 arcsec	0.5 arcsec	1 arcsec
u'	1.05	1.22	1.75
g'	1.05	1.20	1.65
r'	1.20	1.90	3.35
i'	1.30	3.40	> 5
z'	2.40	> 5	> 5

Table 4: The airmass (sec Z) at which the length of the atmospheric dispersion induced 'spectrum' reaches 0.2, 0.5 and 1 arcsec, for the SDSS filters.
Note that the ADC cannot be used in u' band.

has an Atmospheric Dispersion Compensator (ADC). It consists of two sets of counter-rotating prisms with which one can introduce given amounts of dispersion and thus cancel the atmosperic dispersion.

The ADC has good throughput longward of 360nm wavelength; unfortunately this does not include the u' band[1]. At a penalty of slight throughput reduction, use of the ADC can dramatically improve image quality at large zenith angle (see Table 4).

A model for the amount of atmospheric dispersion on Paranal has been calculated by E. Marchetti, see `http://eso.org/gen-fac/pubs/astclim/lasilla/diffrefr.html`. Based on these data, Table 4 shows the airmass at which atmospheric dispersion causes a smearing of the light over a 0.2 arcsec (1 pixel), 0.5 and 1 arcsec length. Depending on the seeing and image quality constraints, use of the ADC at greater airmasses is required.

3.3 OB preparation

Preparing an Observing Block is done with ESO's P2PP tools. An OB consists of a number of templates, each of which represents a standard action taken by the telescope and/or instrument. Each OB should include one *target acquisition template*, whose main role it is to point the telescope at the target, and one or more *science templates* which perform the actual observation. In addition an OB contains a *constraint set* which specifies under which conditions (seeing, transparency, moon phase, timing constraints, ...) the OB may be executed. Full details are given in the P2PP instructions on the ESO web site [**RD5**].

For reasons of flexible scheduling of service mode observations at ESO, the execution time of each OB, including overheads, should be at most one hour. Longer observations need to be split into separate OBs. Unless there are good reasons to do otherwise, OBs should only use one filter each. If filter changes inside an OB are required, it is most efficient to order the exposures in such a way that filters are alternately selected from the two magazines.

To help with planning observations, one can use the Exposure Time Calculator (ETC) from the ESO web site.

3.3.1 Target acquisition

A target acquisition presets the telescope pointing and configures the mirrors, corrector and instrument rotator. In addition it simultaneously prepares the instrument by loading the appropriate filter in the beam, and acquiring guide stars if required.

[1] Note that the atmospheric extinction in u' is high, so observations in this band should in any case be taken as close to zenith as possible.

3.3.2 Scientific exposure

The scientific exposures load an appropriate filter, lock onto the guide stars, perform any offsets, clear the CCD array, open the shutter for the appropriate time, close the shutter and read out the CCD array. A science template may command a number of exposures, possibly interspersed with offsets and filter changes.

3.3.3 Dither and jitter patterns

Different templates are used for observations taken in dither or jitter mode. These templates implement different default offset patterns. The patterns are described in the Template Manual [**RD1**].

3.4 The Observing templates

The detailed use of the templates is described in a separate document. Here the main functionality of the available templates is described.

3.4.1 Target Acquisition Templates

Each OB must start with an acquisition template, whose execution points the telescope and prepares the instrument.

Two acquisition templates are provided: `OCAM_img_acq` and `OCAM_img_acq_movetogap`. Each acquisition template allows specification of the object position, instrument filter for the first exposure, ADC or two-lens corrector, and Cassegrain rotator offset angle. It is also possible to specify a differential tracking rate (for non-sidereal tracking: in this case only the VST guide probe may be used for autoguiding), and whether or not autoguiding is required.

The difference between `OCAM_img_acq` and `OCAM_img_acq_movetogap` is that the former acquires the field 'blind', while the latter takes a short exposure, which the operator can display and use to move the telescope so that a selected bright star falls in a gap between CCDs in order to reduce reflections and remanence.

3.4.2 Science Templates

Science templates perform the actual scientific exposure. For each of these templates the user must specify the Observing Strategy used (see §3.1.2), and the filter to be employed. The templates differ in the number and pattern of offsets that they use.

`OCAM_img_obs_stare` takes a number of exposures through the same filter. The number of integrations, and the integration times (which may be different for the different exposures) are specified. No offsets are made.

`OCAM_img_obs_jitter` performs a jittered exposure (see §3.1.1). The number of exposures, the exposure times, and the step size for the dither pattern can be specified. A step size of 1 arcsec suffices to correct for CCD blemishes. If it is required that a given source is seen by a completely different set of pixels in each sub-exposure, the step size needs to be increased to above that of the sources. This is particularly true if accurate, real-time fringe maps need to be derived from the observations themselves. In those cases *dithering* may be more appropriate.

`OCAM_img_obs_dither` performs a dithered exposure (see §3.1.1). The number of exposures, the exposure times, and the step size for the dither pattern can be specified. The dither patterns are designed

to make sure the full field is observed, without gaps. Two step sizes can be given, one in X (along CCD rows) and one in Y (along columns). It is recommended that these are set to 25 and 85 arcsec, respectively, which are the sizes of the largest gaps in the mosaic.
Two dither patters are provided. The 'diag' pattern simply offsets in X and Y by the step sizes specified, resulting in a diagonal pattern of pointing centers. It results in an optimally homogeneous coverage of the field by the mosaic, for a given number of exposures.
The 'starext' pattern is more complex. It is designed to keep a small area of the field, containing a bright star, off the CCD array in order to reduce reflections. The size of this gap can be specified, recommended values are 8 arcsec $\times$ 8 arcsec. Subject to that constraint this pattern yields the most homogeneous coverage of the field. It works best if the number of exposures is (a multiple of) 5.

The dither and jitter patterns are illustrated in the Template Manual [**RD1**].

`OCAM_img_obs_offset` allows complete flexibility in the definition of offset patterns. The specified number of exposures are taken, and offsets are taken from a list. Offset data are processed in the same way as `OCAM_img_obs_dither` data.

3.4.3 Nighttime Calibration

A number of templates are provided for photometric zero point and atmospheric extinction measurements. Normally these will be used by Observatory staff executing the calibration plan [**RD2**]; these OBs need not be specified as part of a science programme.

`OCAM_img_obs_monit` takes an exposure of a standard field through the composite $u'g'r'i'$ calibration filter.

`OCAM_img_obs_zpkey` takes an exposure of a standard field through one of the key filters (u', g', r', or i', using the two-lens corrector).

`OCAM_img_obs_zpuser` takes an exposure of a standard field through one of the user bands (any other filter, or any filter in combination with the ADC).

3.4.4 Overheads

There are various overheads associated with OmegaCAM observations. Telescope preset to a new target takes about 5 minutes`???`. Filter exchange in the instrument can be done at the same time; it takes between 50 and 110 seconds (the precise value depends on whether a filter is being swapped for another one from the same magazine, or whether they belong in different magazines). Acquisition of guide stars takes `???`s. Reading out the CCDs takes 29s`???`, transferring the data and storing to disk takes a further 12s`???`, and ordering the data into a fits file is complete after a further 20s`???`. Transfer of the data must be complete before the next readout can take place, and all ordering of data must be completed before the next OB can be started.

Table 5 shows the total execution time of the various templates, including overheads associated with CCD readout, telescope and instrument presets, etc.

3.5 Selecting exposure times and number of sub-exposures

The ESO website provides a link to the Exposure Time Calculator (ETC). It may be used to estimate signal-to-noise, count rates, etc., for OmegaCAM observations.

The sky background varies considerably with filter and with moon phase. Table 6 gives the sky count rates per pixel at new, half and full moon. It is important to make sure that the read noise of the

Template	Total execution time (sec)	Comment
`OCAM_img_acq`		
`OCAM_img_acq_movetogap`		
`OCAM_img_obs_stare`		
`OCAM_img_obs_jitter`		
`OCAM_img_obs_dither`		
`OCAM_img_obs_offset`		
N Bias exposures	$20 + N \times 57$	

Table 5: Total execution time, including overheads, associated with the different templates. `To be done`

Filter	electrons per pixel per sec		
	new	half	full
u	3		
g	15		
r	25		
i	35		
z	30		
B	10		
V	15		
Hα	2		

Table 6: Indicative sky count rates through the various filters, at different moon phases.

CCDs (about 5 electrons, equivalent to the noise of a 25 electrons per pixel background) does not add significantly to the sky background noise. Exposure times should ideally be such that the sky background is above 250 electrons per pixel.

If very good seeing is required ($< 0.8''$ `TBC`) then it is best to limit exposure times to 20 minutes or less.

3.6 Special features of the data

OmegaCAM data, as other wide-field CCD imager data, have several features that complicate data analysis. Data reduction software can cope with these, but it is important to be aware of them.

3.6.1 Point Spread Function

Simple description of the PSF variations (after regridding to a sky grid) as measured after commissioning. `TBD with real data.`

3.6.2 CCD blemishes and particle hits

The OmegaCAM CCDs contain a number of cosmetic defects: hot pixels, cold pixels, and traps. The data on these pixels must be masked out before the data can be analysed; if such gaps in the data are unacceptable the observations need to be dithered, or at least jittered. Hot pixels and traps can result in entire columns of data being lost, so jitter/dither offsets must not be parallel to the CCD columns.

In addition, particle hits on the CCDs release charge and obliterate small parts of the image. If these are a concern (their number grows with the exposure time) then several exposures are needed.

3.6.3 Ghosts

Unwanted reflections at air/glass interfaces result in some scattered light in the image. Some of these reflections are reasonably well-focused, resulting in 'ghost' reflections — spurious images from bright sources, appearing in different parts of the field. In OmegaCAM most of these ghosts are very defocused and hence very diffuse, but the most focused one projects to radii of a few mm and so can be expected to be visible if there is a bright star in the field. It arises as a reflection off the entrance surface of the dewar window, followed by a reflection off the nearest filter surface.

Ray tracing calculations predict that a bright star a distance R° degrees from the center of the field will have a ghost that is displaced radially outwards by

$$21''R^\circ + 70''R^{\circ 3} \tag{6}$$

and that this ghost has a diameter of

$$23'' + 73''R^{\circ 2}. \tag{7}$$

At worst, the surface brightness of the ghost of a star of magnitude m is expected to be about $(m + 15)/\mathrm{arcsec}^2$ (two factors of 0.02 for the reflections, spread over an area of 400 arcsec^2).

3.6.4 Sky concentration

Multiple reflections also generate a very defocused image of the field, which is added to the sky background in the image. The effect, usually referred to as 'sky concentration', is a smooth, additive component to each image.

The additive term is also present in flat fields, be it from the sky or from an exposure of the dome screen. If this additive term is not subtracted from the flat fields first, the result of flat-fielding is an image with a flat background but a varying photometric zero point.

3.6.5 Diffraction Spikes

The spider that holds the secondary mirror in place causes diffraction spikes around bright stars. Because the VST is an alt-az telescope, the camera rotates with respect to the spider during an exposure, causing this spike pattern to rotate as well. This will lead to smeared-out wedge-shaped protrusions from bright star images. The motion is fastest, and hence the wedges fattest, when the telescope points near zenith.

In successive exposures the pattern will have a slightly different position angle. It is currently to be decided how these features can be removed during the combination of different exposures.

3.6.6 Fringes

Internal reflections in the CCD and the consequent interference gives rise to fringes in the sky background. These effects show up in the i' and z' bands (and to a low extent in r'), and can have amplitudes up to 30% `TBC` in z' band. The fringes are caused by the emission lines in the night sky spectrum, and can be highly time-variable. As the equivalent width of these lines varies in the sky spectrum so do the fringe amplitudes and to some extent the patterns. This additive effect is mapped by comparing twilight sky exposures (with relatively weak sky emission lines) with dark sky exposures. Appropriately scaling this 'fringe map' to individual exposures then allows the fringe pattern to be subtracted.

3.6.7 Remanence

Exposure to a very bright star can saturate the CCD, and can leave a surplus of charge on the surface of the detector. This can take some time to diffuse away, and meanwhile any subsequent readouts will show a faint residual of the saturated star. Remanence decays away after about `???`s. `more info after full PAE`

4 Calibrating and Reducing OmegaCAM data

All OmegaCAM data are taken in service mode, in the context of a calibration plan [**RD2**] whose function is to maintain the overall calibration of the instrument and atmosphere. Thus the aim is not to calibrate individual data sets, but rather to calibrate the telescope+instrument+sky chain.

Data volumes from OmegaCAM are LARGE. A single exposure leads to 0.5Gbyte of raw data (at 2 bytes per pixel); processed exposures, with a 4-byte real number per pixel, are over a gigabyte in size. Typical data volumes from a single night are 20–50 Gigabytes of raw science data; another 10–20 Gbyte of raw calibration data are also taken every day.

OmegaCAM data are processed using a pipeline (see [**RD3**] for a full description) which is run by the ESO DFS group, and which generates astrometrically and photometrically calibrated images.

All data from OmegaCAM are delivered as multi-extension FITS files. The first extension contains the observing parameters, and extensinos 2–33 contain the data from the individual CCDs. A sample header is given in Appendix D.

4.1 Calibration Plan

The full details of the calibration plan are given in a separate document [**RD2**]. From the point of view of planning or preparing observations with OmegaCAM, we summarise the important features here.

Bias, dark and flat field exposures are taken with a frequency `to be determined by experience`. Flat fields are derived from a combination of twilight exposures and dome screen flat fields, and should be taken within three `TBC` days of the science data. Fringe maps are derived by comparing these flat fields to night-sky exposures.

The photometric zero point is determined as follows. The basic approach is that the atmospheric transparency and instrument efficiency are monitored in four of the SDSS bands ($u'g'r'i'$, the so-called *key bands*) using the two-lens corrector, whereas other filters (so-called *user bands*) are cross-calibrated against these. All filters, including $u'g'r'i'$, are considered as *user bands* when they are used in combination with the Atmospheric Dispersion Corrector (ADC).

OmegaCAM employs a 4-quadrant calibration filter, which is used to monitor the sky transparency and the instrument zero point in $u'g'r'i'$ bands simultaneously. At least three times a night, a standard star field on the celestial pole is observed with this filter to measure atmospheric extinction. Around midnight a high-elevation standard star field is observed with this same calibration filter, and with the monolithic science filters from the SDSS system, and with those user bands in use on a particular night.

Figure 9 shows schematically with what frequencies calibration data are taken.

Astrometric calibration is performed by reference to the many USNO catalogue[2] stars that are present on each CCD. No special calibration observations are needed. With the broadband $g'r'i'z'$ filters and exposure times between 10 seconds and 10 minutes the USNO stars should be unsaturated. Short u' band observations (less than a minute `TBC` may not provide sufficient stars for an accurate astrometric solution.

More specialised calibration files, related e.g. to sky concentration, or fringing from night-sky lines, are derived from the observations themselves, or from less frequent dedicated measurements.

The calibration plan is specified to deliver photometric zero points accurate to 0.05 magnitudes, and

[2]The USNO astrometric star catalogues contain over 400 million stars over the whole sky (an average of 10,000 per square degree, or 300 per OmegaCAM CCD), down to $\sim$ 20th magnitude in R. Typical astrometric uncertainty for each star is $0.3''$ rms. More information on the catalogue can be found at `http://archive.eso.org/skycat/usno.html`.

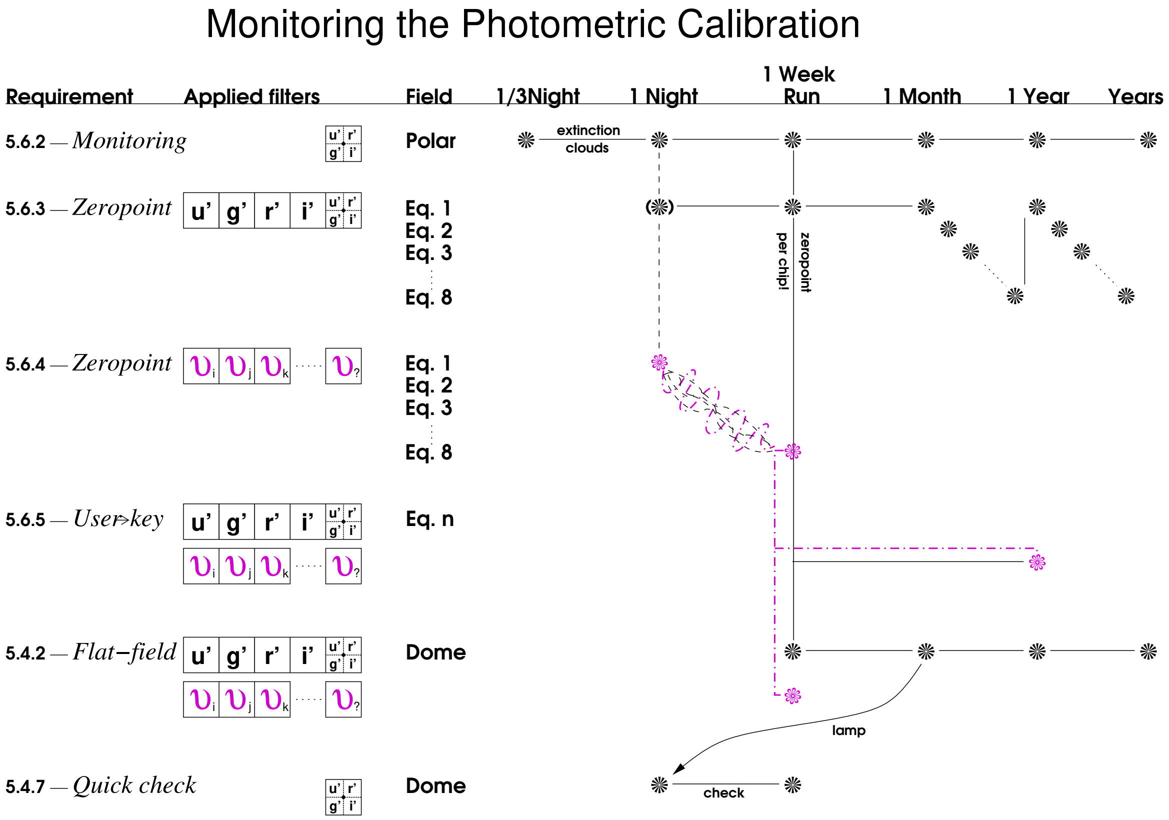

Figure 9: The frequency with which the various types of calibration data are taken. More details are given in the Calibration Plan [**RD2**]. The symbol $\mathcal{U}$ denotes a user band.

astrometry with rms error 0.1 arcsec, in a fully automatic pipeline reduction mode.

4.2 Data reduction Pipeline

Data delivered to the ESO archive consist of the raw exposures, as well as the calibration data. Each PI receives the data (and associated calibration data) taken for their OBs as well as a pipeline-processed data product consisting of calibrated and co-added images for each OB. The header of the image contains the astrometric world coordinate system. The photometric zeropoint is provided as a separate calibration file.

The pipeline performs the following main steps, using calibration files derived by the ESO Data Flow Operations Group in Garching:

1. Each CCD frame is debiased
2. Bad pixels are flagged
3. Cosmic rays and satellite tracks are detected and flagged.
4. Data are divided by a normalised flat field image
5. If appropriate, fringes are removed
6. An astrometric solution is computed for each CCD based on a search of USNO stars in the image
7. Images are background-subtracted, corrected for sky concentration and resampled to a common, linear world coordinate system.
8. Different exposures of the same OB (if taken with the same filter) are combined. Data taken in DITHER and JITTER mode are combined into a single image covering the full field of view, taking into account weights and bad pixel masks. STARE mode data are processed into 32 series (one per CCD) of calibrated exposures without co-addition.

5 TODO's for this manual

1. Update filter bandpasses, zeropts and plot with measured values
2. Insert filter orientations for segmented filters.
3. Update fringe amplitudes with measured values
4. Include bad columns in App C if there are good reasons
5. Present the PlateSystem (both for DFS and for planning observations?)
6. How to handle diffraction spikes
7. Insert a real fits header in App E.

A Filter throughput curves

B Detector response curves

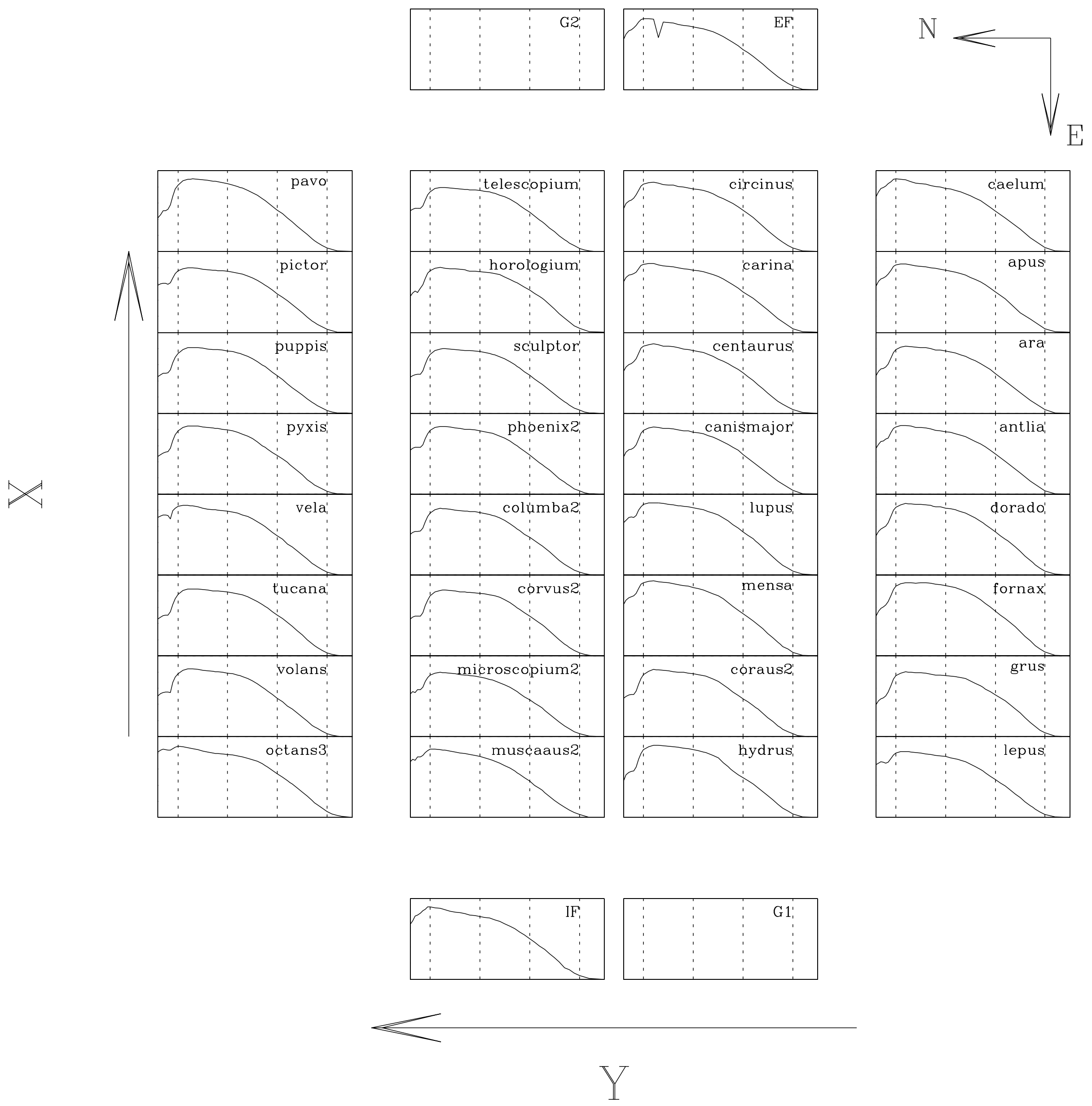

Figure 10: The QE curves for all CCDs in the mosaic, laid out as the mosaic itself. The solid curve in each panel is the measured QE for that device; the dotted curve is the average for all 32 science CCDs. The wavelength range from 320 to 1100nm is plotted; dotted lines indicate 400, 600, 800 and 1000nm. X and Y are coordinates in the focal plane; for the default instrument rotator position angle of 0 X points West and Y points North. `To be updated?`

C Bad column lists

D Sample FITS header

Below follows a sample header for an OmegaCAM image. `To be updated with a real header for a 32-chip image!`

```
Header listing for HDU #1:
SIMPLE  =                    T          / Standard FITS format (NOST-100.0)
BITPIX  =                   16          / # of bits storing pix values
NAXIS   =                    0          / # of axes in frame
ORIGIN  = 'TEST    '                    / European Southern Observatory
DATE    = '2004-02-12T15:25:07.041'     / UT date when this file was written
TELESCOP= 'Tel name not set'            / ESO Telescope Name
INSTRUME= 'OCAM    '                    / Instrument used.
RA      =             0.039774          / 00:00:09.5 RA (J2000) pointing (deg)
DEC     =            -85.00297          / -85:00:10.6 DEC (J2000) pointing (deg)
EQUINOX =                2000.          / Standard FK5 (years)
RADECSYS= 'FK5     '                    / Coordinate reference frame
EXPTIME =               5.0000          / Total integration time
MJD-OBS =       53047.64241470          / MJD start (2004-02-12T15:25:04.630)
DATE-OBS= '2004-02-12T15:25:04.630'     / Date of observation
UTC     =            51437.372          / 14:17:17.372 UTC at start (sec)
LST     =            68379.192          / 18:59:39.192 LST at start (sec)
EXTEND  =                    T / Auto Added Keyword
HIERARCH ESO ADA ABSROT END  =      0.00000 / Abs rot angle at exp end (deg)
HIERARCH ESO ADA ABSROT PPOS = 'POS     '   / sign of probe position
HIERARCH ESO ADA ABSROT START=      0.00000 / Abs rot angle at exp start (deg)
HIERARCH ESO ADA GUID DEC    =      0.00000 / 00:00:00.0 Guide star DEC J2000
HIERARCH ESO ADA GUID RA     =     0.000000 / 00:00:00.0 Guide star RA J2000
HIERARCH ESO ADA GUID STATUS = 'ON      '   / Status of autoguider
HIERARCH ESO ADA POSANG      =      0.00000 / Position angle at start
HIERARCH ESO DET BITS        =           16 / Bits per pixel readout
HIERARCH ESO DET CHIPS       =           16 / # of chips in detector array
HIERARCH ESO DET DATE        = '10 March 03' / Installation date
HIERARCH ESO DET DEC         =   0.00000000 / Apparent 00:00:00.0 DEC at start
HIERARCH ESO DET DID         = 'ESO-VLT-DIC.CCDDCS,ESO-VLT-DIC.FCDDCS' / Diction
HIERARCH ESO DET EXP NO      =            1 / Unique exposure ID number
HIERARCH ESO DET EXP RDTTIME =        0.110 / image readout time
HIERARCH ESO DET EXP TYPE    = 'Normal  '   / Exposure type
HIERARCH ESO DET EXP XFERTIM =       77.166 / image transfer time
HIERARCH ESO DET FRAM ID     =            1 / Image sequencial number
HIERARCH ESO DET FRAM TYPE   = 'Normal  '   / Frame type
HIERARCH ESO DET ID          = '        '   / Detector system Id
HIERARCH ESO DET NAME        = 'ocmsci1 - ocmsci1' / Name of detector system
HIERARCH ESO DET OUTPUTS     =           16 / # of outputs
HIERARCH ESO DET OUTREF      =            0 / reference output
HIERARCH ESO DET RA          =   0.00000000 / Apparent 00:00:00.0 RA at start
HIERARCH ESO DET READ CLOCK  = 'mosaic read (ord' / Readout clock pattern used
HIERARCH ESO DET READ MODE   = 'normal  '   / Readout method
HIERARCH ESO DET READ NFRAM  =            1 / Number of readouts buffered in sin
HIERARCH ESO DET READ SPEED  = 'normal  '   / Readout speed
HIERARCH ESO DET SOFW MODE   = 'Lcu simulated' / CCD sw operational mode
HIERARCH ESO DET WIN1 BINX   =            1 / Binning factor along X
HIERARCH ESO DET WIN1 BINY   =            1 / Binning factor along Y
HIERARCH ESO DET WIN1 DIT1   =     0.000000 / actual subintegration time
```

```
HIERARCH ESO DET WIN1 DKTM   =       0.0010 / Dark current time
HIERARCH ESO DET WIN1 NDIT   =            1 / # of subintegrations
HIERARCH ESO DET WIN1 NX     =         8184 / # of pixels along X
HIERARCH ESO DET WIN1 NY     =        16392 / # of pixels along Y
HIERARCH ESO DET WIN1 ST     =            T / If T, window enabled
HIERARCH ESO DET WIN1 STRX   =            1 / Lower left pixel in X
HIERARCH ESO DET WIN1 STRY   =            1 / Lower left pixel in Y
HIERARCH ESO DET WIN1 UIT1   =     5.000000 / user defined subintegration time
HIERARCH ESO DET WINDOWS     =            1 / # of windows readout
HIERARCH ESO DPR CATG        = 'SCIENCE '   / Observation category
HIERARCH ESO DPR TECH        = 'IMAGE   '   / Observation technique
HIERARCH ESO DPR TYPE        = 'OBJECT  '   / Observation type
HIERARCH ESO INS DATE        = '2002-01-31' / Instrument release date (yyyy-mm-d
HIERARCH ESO INS DID         = 'ESO-VLT-DIC.OCAM_ICS-1.20' / Data dictionary for
HIERARCH ESO INS FILT1 ID    = 'PS7     '   / Filter unique id.
HIERARCH ESO INS FILT1 NAME  = 'V_JOHN  '   / Filter name.
HIERARCH ESO INS FILT1 NO    =            8 / Filter position.
HIERARCH ESO INS FILT1 SWSIM =            T / If T, function is software simulat
HIERARCH ESO INS ID          = 'OCAM/1.55'  / Instrument ID.
HIERARCH ESO INS LAMP1 SWSIM =            T / If T, function is software simulat
HIERARCH ESO INS LAMP2 SWSIM =            T / If T, function is software simulat
HIERARCH ESO INS MODE        = 'IMAGING '   / Instrument mode used.
HIERARCH ESO INS SENS1 ID    = 'LCUR    '   / sensor ID.
HIERARCH ESO INS SENS1 NAME  = 'Lamps current' / sensor common name.
HIERARCH ESO INS SENS1 VAL   =  9999.000000 / Sensor numeric value.
HIERARCH ESO INS SENS2 ID    = 'FCFL1   '   / sensor ID.
HIERARCH ESO INS SENS2 NAME  = 'Flow of Cooling Fluid IN Instrum' / sensor commo
HIERARCH ESO INS SENS2 VAL   =  9999.000000 / Sensor numeric value.
HIERARCH ESO INS SENS3 ID    = 'FCFL2   '   / sensor ID.
HIERARCH ESO INS SENS3 NAME  = 'Flow of Cooling Fluid OUT of Ins' / sensor commo
HIERARCH ESO INS SENS3 VAL   =  9999.000000 / Sensor numeric value.
HIERARCH ESO INS SENSOR1 SWSIM=           T / If T, function is software simulat
HIERARCH ESO INS SENSOR2 SWSIM=           T / If T, function is software simulat
HIERARCH ESO INS SENSOR3 SWSIM=           T / If T, function is software simulat
HIERARCH ESO INS SENSOR4 SWSIM=           T / If T, function is software simulat
HIERARCH ESO INS SENSOR5 SWSIM=           T / If T, function is software simulat
HIERARCH ESO INS SHUT1 SWSIM =            T / If T, function is software simulat
HIERARCH ESO INS SWSIM       = 'NORMAL  '   / Software simulation.
HIERARCH ESO INS TEMP11 ID   = 'TFS     '   / Temperature sensor ID.
HIERARCH ESO INS TEMP11 NAME = 'Temp. Filter System' / Temperature sensor name.
HIERARCH ESO INS TEMP11 VAL  =       9999.0 / Temperature sensor numeric value.
HIERARCH ESO INS TEMP12 ID   = 'TFCL1   '   / Temperature sensor ID.
HIERARCH ESO INS TEMP12 NAME = 'Temp. FIERA Cooling Liquid #1' / Temperature sen
HIERARCH ESO INS TEMP12 VAL  =       9999.0 / Temperature sensor numeric value.
HIERARCH ESO INS TEMP13 ID   = 'TFCL2   '   / Temperature sensor ID.
HIERARCH ESO INS TEMP13 NAME = 'Temp. FIERA Cooling Liquid #2' / Temperature sen
HIERARCH ESO INS TEMP13 VAL  =       9999.0 / Temperature sensor numeric value.
HIERARCH ESO INS TEMP21 ID   = 'FCST1   '   / Temperature sensor ID.
HIERARCH ESO INS TEMP21 NAME = 'Top heat exchanger set value (TC' / Temperature
HIERARCH ESO INS TEMP21 REF  =       9999.0 / Temperature sensor reference value
HIERARCH ESO INS TEMP21 VAL  =       9999.0 / Temperature sensor numeric value.
HIERARCH ESO INS TEMP22 ID   = 'FCST2   '   / Temperature sensor ID.
HIERARCH ESO INS TEMP22 NAME = 'Bottom heat exchanger set value' / Temperature s
HIERARCH ESO INS TEMP22 REF  =       9999.0 / Temperature sensor reference value
HIERARCH ESO INS TEMP22 VAL  =       9999.0 / Temperature sensor numeric value.
```

```
HIERARCH ESO INS TEMP23 ID   = 'FCST3   '   / Temperature sensor ID.
HIERARCH ESO INS TEMP23 NAME = 'Lower level filling sensors set' / Temperature s
HIERARCH ESO INS TEMP23 REF  =       9999.0 / Temperature sensor reference value
HIERARCH ESO INS TEMP23 VAL  =       9999.0 / Temperature sensor numeric value.
HIERARCH ESO INS TEMP24 ID   = 'FCST4   '   / Temperature sensor ID.
HIERARCH ESO INS TEMP24 NAME = 'Upper level filling sensor set v' / Temperature
HIERARCH ESO INS TEMP24 REF  =       9999.0 / Temperature sensor reference value
HIERARCH ESO INS TEMP24 VAL  =       9999.0 / Temperature sensor numeric value.
HIERARCH ESO INS TEMP25 ID   = 'FCST5   '   / Temperature sensor ID.
HIERARCH ESO INS TEMP25 NAME = 'Sorption pump set value (TC5)' / Temperature sen
HIERARCH ESO INS TEMP25 REF  =       9999.0 / Temperature sensor reference value
HIERARCH ESO INS TEMP25 VAL  =       9999.0 / Temperature sensor numeric value.
HIERARCH ESO INS TEMP26 ID   = 'FCST6   '   / Temperature sensor ID.
HIERARCH ESO INS TEMP26 NAME = 'LN2 gas buffer container set val' / Temperature
HIERARCH ESO INS TEMP26 REF  =       9999.0 / Temperature sensor reference value
HIERARCH ESO INS TEMP26 VAL  =       9999.0 / Temperature sensor numeric value.
HIERARCH ESO INS TEMP27 ID   = 'FCST7   '   / Temperature sensor ID.
HIERARCH ESO INS TEMP27 NAME = 'Active shield set value (TC7)' / Temperature sen
HIERARCH ESO INS TEMP27 REF  =       9999.0 / Temperature sensor reference value
HIERARCH ESO INS TEMP27 VAL  =       9999.0 / Temperature sensor numeric value.
HIERARCH ESO OBS DID         = 'ESO-VLT-DIC.OBS-1.7' / OBS Dictionary
HIERARCH ESO OBS GRP         = '0       '   / linked blocks
HIERARCH ESO OBS ID          =           -1 / Observation block ID
HIERARCH ESO OBS NAME        = 'Maintenance' / OB name
HIERARCH ESO OBS PI-COI ID   =            0 / ESO internal PI-COI ID
HIERARCH ESO OBS PI-COI NAME = 'Condor  '   / PI-COI name
HIERARCH ESO OBS PROG ID     = 'Maintenance' / ESO program identification
HIERARCH ESO OBS START       = '2004-02-12T15:24:55' / OB start time
HIERARCH ESO OBS TPLNO       =            1 / Template number within OB
HIERARCH ESO OCS DET1 IMGNAME= 'OCAM_IMG_OBS' / Data File Name.
HIERARCH ESO TEL AIRM END    =        0.000 / Airmass at end
HIERARCH ESO TEL AIRM START  =        0.000 / Airmass at start
HIERARCH ESO TEL ALT         =       89.000 / Alt angle at start (deg)
HIERARCH ESO TEL AMBI FWHM END=        0.00 / Observatory Seeing queried from AS
HIERARCH ESO TEL AMBI FWHM START=      0.00 / Observatory Seeing queried from AS
HIERARCH ESO TEL AMBI PRES END=      750.00 / Observatory ambient air pressure q
HIERARCH ESO TEL AMBI PRES START=    750.00 / Observatory ambient air pressure q
HIERARCH ESO TEL AMBI RHUM   =          12. / Observatory ambient relative humi
HIERARCH ESO TEL AMBI TEMP   =        10.00 / Observatory ambient temperature qu
HIERARCH ESO TEL AMBI WINDDIR=           0. / Observatory ambient wind directio
HIERARCH ESO TEL AMBI WINDSP =        10.00 / Observatory ambient wind speed que
HIERARCH ESO TEL AZ          =      354.993 / Az angle at start (deg) S=0,W=90
HIERARCH ESO TEL CHOP ST     =            F / True when chopping is active
HIERARCH ESO TEL DATE        = '2099-12-31T01:02:03.456' / TCS installation date
HIERARCH ESO TEL DID         = 'ESO-VLT-DIC.TCS' / Data dictionary for TEL
HIERARCH ESO TEL DOME STATUS = 'FULLY-OPEN' / Dome status
HIERARCH ESO TEL FOCU ID     = 'CA      '   / Telescope focus station ID
HIERARCH ESO TEL FOCU LEN    =      108.827 / Focal length (m)
HIERARCH ESO TEL FOCU SCALE  =        1.894 / Focal scale (arcsec/mm)
HIERARCH ESO TEL FOCU VALUE  =        1.000 / M2 setting (mm)
HIERARCH ESO TEL GEOELEV     =        2648. / Elevation above sea level (m)
HIERARCH ESO TEL GEOLAT      =     -24.6259 / Tel geo latitute (+=North) (deg)
HIERARCH ESO TEL GEOLON      =     -70.4032 / Tel geo longitude (+=East) (deg)
HIERARCH ESO TEL ID          = 'v 1.83  '   / TCS version number
HIERARCH ESO TEL MOON DEC    =      0.00000 / 00:00:00.0 DEC (J2000) (deg)
```

```
HIERARCH ESO TEL MOON RA     =     0.000000 / 00:00:00.0 RA (J2000) (deg)
HIERARCH ESO TEL OPER        = 'Operator name not set' / Telescope Operator
HIERARCH ESO TEL PARANG END  =        0.000 / Parallactic angle at end (deg)
HIERARCH ESO TEL PARANG START=        0.000 / Parallactic angle at start (deg)
HIERARCH ESO TEL TH M1 TEMP  =         0.00 / M1 superficial temperature
HIERARCH ESO TEL TRAK STATUS = 'OFF     '   / Tracking status
HIERARCH ESO TPL DID         = 'ESO-VLT-DIC.TPL-1.4' / Data dictionary for TPL
HIERARCH ESO TPL EXPNO       =            1 / Exposure number within template
HIERARCH ESO TPL ID          = 'OCAM_img_obs_dither' / Template signature ID
HIERARCH ESO TPL NAME        = 'OCAM dither mode sequence' / Template name
HIERARCH ESO TPL NEXP        =            5 / Number of exposures within templat
HIERARCH ESO TPL PRESEQ      = 'OCAM_img_obs_dither.seq' / Sequencer script
HIERARCH ESO TPL START       = '2004-02-12T15:24:55' / TPL start time
HIERARCH ESO TPL VERSION     = '1.0     '   / Version of the template
END

Header listing for HDU #2:
XTENSION= 'IMAGE   '                        / Extension first keyword (see SIMPLE)
BITPIX  =                   16          / # of bits storing pix values
NAXIS   =                    2          / # of axes in frame
NAXIS1  =                 2046          / # pixels/axis
NAXIS2  =                 4098          / # pixels/axis
PCOUNT  =                    0          / Number of parameters per group
GCOUNT  =                    1          / Number of groups
EXTNAME = 'ccd50   '                        / Extension name
BZERO   =              32768.0          / pixel=FITS*BSCALE+BZERO
BSCALE  =                  1.0          / pixel=FITS*BSCALE+BZERO
ORIGIN  = 'ESO     '                        / European Southern Observatory
DATE    = '2004-02-12T15:25:07.041'     / UT date when this file was written
EXPTIME =               5.0000          / Total integration time
MJD-OBS =       53047.64241470          / MJD start (2004-02-12T15:25:04.630)
DATE-OBS= '2004-02-12T15:25:04.630'     / Date of observation
CTYPE1  = 'PIXEL   '                        / Pixel coordinate system
CTYPE2  = 'PIXEL   '                        / Pixel coordinate system
CRVAL1  =                  1.0          / value of ref pixel
CRVAL2  =                  1.0          / value of ref pixel
CRPIX1  =                  1.0          / Ref. pixel of center of rotation
CRPIX2  =              -4097.0          / Ref. pixel of center of rotation
CDELT1  =                  1.0          / Binning factor
CDELT2  =                  1.0          / Binning factor
HIERARCH ESO DET CHIP1 DATE  = '1998-12-12' / Date of installation [YYYY-MM-DD]
HIERARCH ESO DET CHIP1 ID    = 'ccd50   '   / Detector chip identification
HIERARCH ESO DET CHIP1 INDEX =            1 / Chip index
HIERARCH ESO DET CHIP1 NAME  = 'EEVCCD44-90' / Detector chip name
HIERARCH ESO DET CHIP1 NX    =         2046 / # of pixels along X
HIERARCH ESO DET CHIP1 NY    =         4098 / # of pixels along Y
HIERARCH ESO DET CHIP1 PSZX  =         15.0 / Size of pixel in X
HIERARCH ESO DET CHIP1 PSZY  =         15.0 / Size of pixel in Y
HIERARCH ESO DET CHIP1 X     =            1 / X location in array
HIERARCH ESO DET CHIP1 XGAP  =     0.000000 / Gap between chips along x
HIERARCH ESO DET CHIP1 Y     =            2 / Y location in array
HIERARCH ESO DET CHIP1 YGAP  =     0.000000 / Gap between chips along y
HIERARCH ESO DET OUT1 CHIP   =            1 / Chip to which the output belongs
HIERARCH ESO DET OUT1 CONAD  =         2.24 / Conversion from ADUs to electrons
HIERARCH ESO DET OUT1 GAIN   =         0.45 / Conversion from electrons to ADU
```

```
HIERARCH ESO DET OUT1 ID     = 'L       '   / Output ID as from manufacturer
HIERARCH ESO DET OUT1 INDEX  =            1 / Output index
HIERARCH ESO DET OUT1 NAME   = 'L       '   / Description of output
HIERARCH ESO DET OUT1 NX     =         2046 / valid pixels along X
HIERARCH ESO DET OUT1 NY     =         4098 / valid pixels along Y
HIERARCH ESO DET OUT1 OVSCX  =            0 / Overscan region in X
HIERARCH ESO DET OUT1 OVSCY  =            0 / Overscan region in Y
HIERARCH ESO DET OUT1 PRSCX  =            0 / Prescan region in X
HIERARCH ESO DET OUT1 PRSCY  =            0 / Prescan region in Y
HIERARCH ESO DET OUT1 RON    =         0.00 / Readout noise per output (e-)
HIERARCH ESO DET OUT1 X      =            1 / X location of output
HIERARCH ESO DET OUT1 Y      =         8196 / Y location of output
END

Header listing for HDU #3:

...

...



Header listing for HDU #17:
XTENSION= 'IMAGE   '                      / Extension first keyword (see SIMPLE)
BITPIX  =                   16            / # of bits storing pix values
NAXIS   =                    2            / # of axes in frame
NAXIS1  =                 2046            / # pixels/axis
NAXIS2  =                 4098            / # pixels/axis
PCOUNT  =                    0            / Number of parameters per group
GCOUNT  =                    1            / Number of groups
EXTNAME = 'ccd54   '                      / Extension name
BZERO   =              32768.0            / pixel=FITS*BSCALE+BZERO
BSCALE  =                  1.0            / pixel=FITS*BSCALE+BZERO
ORIGIN  = 'ESO     '                      / European Southern Observatory
DATE    = '2004-02-12T15:25:06.982'      / UT date when this file was written
EXPTIME =               5.0000            / Total integration time
MJD-OBS =       53047.64241343            / MJD start (2004-02-12T15:25:04.520)
DATE-OBS= '2004-02-12T15:25:04.520'      / Date of observation
CTYPE1  = 'PIXEL   '                      / Pixel coordinate system
CTYPE2  = 'PIXEL   '                      / Pixel coordinate system
CRVAL1  =                  1.0            / value of ref pixel
CRVAL2  =                  1.0            / value of ref pixel
CRPIX1  =              -6137.0            / Ref. pixel of center of rotation
CRPIX2  =                  1.0            / Ref. pixel of center of rotation
CDELT1  =                  1.0            / Binning factor
CDELT2  =                  1.0            / Binning factor
HIERARCH ESO DET CHIP8 DATE  = '1998-12-12' / Date of installation [YYYY-MM-DD]
HIERARCH ESO DET CHIP8 ID    = 'ccd54   '   / Detector chip identification
HIERARCH ESO DET CHIP8 INDEX =            8 / Chip index
HIERARCH ESO DET CHIP8 NAME  = 'EEVCCD44-90' / Detector chip name
HIERARCH ESO DET CHIP8 NX    =         2046 / # of pixels along X
HIERARCH ESO DET CHIP8 NY    =         4098 / # of pixels along Y
HIERARCH ESO DET CHIP8 PSZX  =         15.0 / Size of pixel in X
HIERARCH ESO DET CHIP8 PSZY  =         15.0 / Size of pixel in Y
HIERARCH ESO DET CHIP8 X     =            4 / X location in array
```

```
HIERARCH ESO DET CHIP8 XGAP  =     0.000000 / Gap between chips along x
HIERARCH ESO DET CHIP8 Y     =            1 / Y location in array
HIERARCH ESO DET CHIP8 YGAP  =     0.000000 / Gap between chips along y
HIERARCH ESO DET OUT1 CHIP   =            8 / Chip to which the output belongs
HIERARCH ESO DET OUT1 CONAD  =         0.00 / Conversion from ADUs to electrons
HIERARCH ESO DET OUT1 GAIN   =         0.00 / Conversion from electrons to ADU
HIERARCH ESO DET OUT1 ID     = '        '   / Output ID as from manufacturer
HIERARCH ESO DET OUT1 INDEX  =           15 / Output index
HIERARCH ESO DET OUT1 NAME   = 'L       '   / Description of output
HIERARCH ESO DET OUT1 NX     =         2046 / valid pixels along X
HIERARCH ESO DET OUT1 NY     =         4098 / valid pixels along Y
HIERARCH ESO DET OUT1 OVSCX  =            0 / Overscan region in X
HIERARCH ESO DET OUT1 OVSCY  =            0 / Overscan region in Y
HIERARCH ESO DET OUT1 PRSCX  =            0 / Prescan region in X
HIERARCH ESO DET OUT1 PRSCY  =            0 / Prescan region in Y
HIERARCH ESO DET OUT1 RON    =         0.00 / Readout noise per output (e-)
HIERARCH ESO DET OUT1 X      =         8184 / X location of output
HIERARCH ESO DET OUT1 Y      =            1 / Y location of output
END
```