

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 1

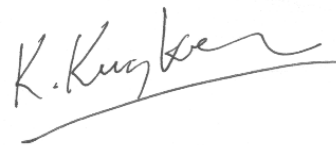
OmegaCAM

OmegaCAM Data Reduction Specifications

Implementation specifications for data reduction software

Issue: VERSION 1.1
Date: 29 Oct 2001
Prepared by: Rengelink, Deul, Begeman, Boxhoorn, Valentijn
Purpose of printout: FDR

Approved by:



Konrad Kuijken, OmegaCAM PI.



Edwin Valentijn, NOVA programme manager.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 2

Selected items from 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	

www.astro.rug.nl/~omegacam

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 3

Table of Contents

1 INTRODUCTION 5

 1.3 Reference documents 6

 1.4 Abbreviations and Acronyms 7

2 Scientific requirements - See URD 9

3 Instrument concept - see URD 9

4 **OmegaCAM** OBSERVING STRATEGIES - see URD 9

5 DATA REDUCTION SPECIFICATIONS 10

 5.0 Documentation system, **Odoco**-see URD 10

 5.2.1 Req.- *CCD read noise - doit* 13

 5.2.2 Req.- *hot pixels* 14

 5.2.3 Req.- *CCD gain* 15

 5.2.4 Req.- *Electromagnetic Compatibility* 16

 5.2.5 Req.- *Electrical cross talk* 17

 5.3.1 Req.- *CCD Dark Current - doit* 17

 5.3.2 Req.- *CCD Particle Event Rate* 18

 5.3.3 Req.- *CCD Linearity* 19

 5.3.4 Req.- *CCD Charge Transfer Efficiency* 20

 5.3.5 Req.- *CCD Cold Pixels* 21

 5.3.6 Req.- *CCD Hysteresis, strong signal* 22

 5.4.1 Req.- *Bias - doit* 22

 5.4.2 Req.- *Flat-field - dome key bands + user bands - doit* 24

 5.4.3 Req.- *Flat-field - twilight* 25

 5.4.4 Req.- *Flat-field - night sky* 26

 5.4.5 Req.- *Flat-field - Fringing* 28

 5.4.6 Req.- *Flat-field - master flat and weight map* 28

 5.4.7 Req.- *Quick detector responsivity check - doit* 29

 5.4.8 Req.- *Illumination correction* 30

 5.5.1 Req.- *Position of Camera in focal plane* 31

 5.5.2 Req.- *Telescope Pointing* 31

 5.5.3 Req.- *Telescope and Field Rotator tracking* 31

 5.5.4 Req.- *PSF Anisotropy* 33

 5.5.5 Req.- *The astrometric solution for templates - see 6.3.4* 33

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 4

- 5.5.6 Req.– *The astrometric solution for Guide CCD’s* 33
- 5.6.1 Req.– *Shutter Timing* 34
- 5.6.2 Req.– *Photometric Calibration - monitoring* 35
- 5.6.3 Req.– *Photometric Calibration - zeropoint key bands -doit* .. 37
- 5.6.4 Req.– *Photometric Calibration - zeropoint user bands*..... 39
- 5.6.5 Req.– *Filter band passes - user bands vs key bands*..... 40
- 5.6.6 Req.– *Dependency on rotator angle/reproducibility*..... 40
- 5.6.7 Req.– *Linearity (as a function of flux)*..... 41
- 5.6.8 Req.– *Detection limit and ETC calibrations*..... 41
- 5.6.9 Req.– *Secondary Standards*..... 42
- 5.7.1 Req.– *Camera focus/tilt*..... 42
- 5.7.2 Req.– *Ghosts - ADC*..... 43
- Fig 6. Data Flow of Science and Calibration data 44
- 6 DATA REDUCTION SOFTWARE SPECIFICS 45
 - 6.1 Data reduction software requirements 45
 - 6.2 Estimate of data volumes 54
 - 6.3 Specifications of the Image Pipeline 55
 - 6.3.1 Seq.– *Initialization and image statistics* 58
 - 6.3.2 Seq.– *Trim, de-bias, flatfield* 60
 - 6.3.3 Seq.– *Construct individual weights* 60
 - 6.3.4 Seq.– *Astrometric calibration*..... 62
 - 6.3.5 Seq.– *Apply photometric calibration* 64
 - 6.3.6 Seq.– *Co-addition*..... 65
- 7 NEEDED FUNCTIONALITIES 69
 - 7.1 Image manipulation 69
 - 7.2 Catalog manipulation 72
 - 7.3 Header manipulation 77
 - 7.4 Miscellaneous functionalities 78
- A1 LIST of CALIBRATION REQUIREMENTS 79
- A2 LIST of RAW CALIBRATION DATA 81
- A3 LIST of DFS I/O CALIBRATION FILES 82
- A4 LIST of DFS INPUT REFERENCE CATALOGUES 84
- A5 LIST of SEQUENTIAL STEPS in IMAGE PIPELINE 85

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 5

1 INTRODUCTION

The Data Reduction Specification document (DRS) follows the **OmegaCAM** User Requirement Document (URD) and the **OmegaCAM** Calibration Plan (CP). While the URD presents the top level requirements for science observations and baseline requirements for calibrating the observations, the CP specifies the detailed implementation of the baseline calibration requirements in terms of Calibration Observations and calibration tasks. The present document specifies the specific data reduction tasks associated with these calibration tasks. It also specifies all data reduction tasks to "remove the instrument signature from the raw data".

The document intends to give a complete map of the **recipes, functionalities** and **CalFile**– s needed for the reduction of the **OmegaCAM** raw calibration and science data, higher level objectives, etc., being given in the URD and CP.

This document forms the skeleton of the deliverable Data Reduction Specifications (VLT-SPE-ESO-19000-1618). It specifies the definition and naming of recipes and the relation to the various input and output files and the observing templates. Because data taking and reduction of **OmegaCAM** is highly procedurized, the actual implementation of the data reduction procedures will to closely follow the specifications given here. Tasks which are expected to be done only once, for which high level procedurizing would be counter productive, will be done with an interactive analysis and are indicated as such.

In Section 5 the recipes and other data reduction related items of all calibration related tasks are specified. Section 6 specifies the recipe for the reduction of the raw image data into astrometrically and photometrically calibrated images. Section 7 summarizes the various low level functionalities required to operate the recipes.

The present documentation is a part of the **Odoco** documentation system and will evolve in the coming years, under configuration control, its constraints are set by the Baseline requirements given in the URD.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 6

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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 7

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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 8

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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 9

2 Scientific requirements - See URD

3 Instrument concept - see URD

4 OmegaCAM OBSERVING STRATEGIES - see URD

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 10

5 DATA REDUCTION SPECIFICATIONS of CALIBRATION TASKS

5.0 Documentation system, Odoco-see URD

Notes for reading the DRS Section 5.

- i) On request, we have not repeated the information on requirements given in the URD and CP, the present document being focussed on the bare data reduction implementation issues. For implementation work, when desired, it is however possible to provide a print-out of the various requirements with a more extensive set of items.
- ii) Note, that when a certain item is not printed in the text, this means that it is considered to be non-relevant, *e.g.* the item **recipe** does not appear when there is no dedicated recipe for the requirement.
- iii) For some tasks, which are seldom done, no detailed recipes are written, but instead the data reduction will use an **interactive analysis**.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 11

LAY-OUT of BASIC CALIBRATION REQUIREMENTS DETECTOR RELATED

5.1	Functional Checks	
5.2	Electronics specific	
5.2.1	CCD read noise - <i>doit</i>	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 - <i>doit</i>	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 - <i>doit</i>	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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 12

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 - <i>doit</i>	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 <i>doit</i>	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	

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 13

5.2.1 Req. — *CCD read noise - doit*

Recipe:

Recipe– Read_Noise

Inputs:

2 raw bias frames

CalFile– 521 *Readout noise* older versions

Outputs:

CalFile– 521 *Readout noise* in ADU's

Required accuracy, constraints:

Readout noise less than $5e^-$.

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

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

TSF:

Mode– Stare N=2

(**TSF– OCM_img_cal_bias**, N=2)

= **TSF– OCM_img_cal_readnoise**

Needed functionality:

image arithmetic; image statistics

CA:

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

Reject 3σ outliers.

CAP:

ADD trendanalysis

input: bias1, bias2, previous_read_noise

```
diff = bias1-bias2
```

```
imstat = diff.Stat(reject_method='sigma',
    reject_level=3, niter=2))
```

```
read_noise = imstat.rms/SQRT(2)
```

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 14

```
if abs(previous_read_noise/read_noise-1) > MAXIMUM_CHANGE:
    print 'WARNING - Large variation in read_noise'
```

```
output: read_noise
```

5.2.2 Req. — *hot pixels*

Recipe:

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

Inputs:

CalFile– 541 *Master bias*

CalFile– 522 *Bad/hot pixel map* previous version

Outputs:

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

Required accuracy, constraints:

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

TSF:

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

Needed functionality:

image - statistics; image - mask

CA:

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

CAP:

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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 15

```

if imstat.total_flux-prev_hot_pixel_map_stats.total_flux >
    MAX_NEW_HOT_PIXELS:
    print 'WARNING - Too many new hot pixels'
output hot_pixel_map, imstat

```

5.2.3 Req. — CCD gain

Recipe:

Recipe– Gain

Inputs:

CalFile– 521 *Read noise*

CalFile– 541 *Master bias frame*

CalFile– 523 *Conversion factor e^-/ADU older versions.*

Outputs:

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

Required accuracy, constraints:

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

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

TSF:

Mode– Stare N=20

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

= TSF– OCM_img_cal_gain

Needed functionality:

image - arithmetic; image - statistics; misc - regression

CA:

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

CAP:

```

input gain_list, bias, shutter_map
sum_list = []

```

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 16

```

diff_list = []

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

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

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

output regression_coeff

```

5.2.4 Req. — *Electromagnetic Compatibility*

Inputs:

raw bias frames, obtained when telescope/dome were moving.

CalFile– 521 *CCD read noise*

Outputs:

OK/non-conformance flag.

Required accuracy, constraints:

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

TSF:

Mode– Stare N=2

TSF– OCM_img_cal_bias while telescope and/or dome are moving.

Needed functionality:

image arithmetic; image statistics

CA:

The operational read noise is compared to **CalFile– 521** *CCD read noise* (see req.521 for implementation details). The difference should be measured

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 17

with an accuracy of 5%.

CAP:

(see req.521 for implementation details)

5.2.5 Req. — *Electrical cross talk*

Outputs:

Conformance flag

Required accuracy, constraints:

10^{-5}

TSF:

Mode– Stare N=1

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

5.3.1 Req. — *CCD Dark Current - doit*

Recipe:

Recipe– Dark_Current

Inputs:

Lab values

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

CalFile– 532 *Particle event rate older version.*

Outputs:

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

CalFile– 532 *Particle event rate in ADU/cm²/hour*

Required accuracy, constraints:

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

Accuracy of determining particle event rate 1 ADU/cm²/hour.

Particle event rates should be identical for each chip.

TSF:

Mode– Stare N=3

TSF– OCM_img_cal_dark exposure time 1 hour each, shutter closed. Dome lamp on-off-on

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 18

Needed functionality:

image - trim; image - median average, image - arithmetic, image - masking

CA:

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

CAP:

```
input dark_list

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

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

5.3.2 Req. — CCD Particle Event Rate

Recipe:

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

Outputs:

CalFile– 532 *Particle event rate* in ADU/cm²/hour

Required accuracy, constraints:

better than 1 ADU/cm²/hour

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 19

CA:

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

CAP:

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

5.3.3 Req. — CCD Linearity

Recipe:

Recipe– Gain, see also **req. 523** *CCD Gain*

Inputs:

CalFile– 541 *Bias*

RawData– 523 *CCD Gain*

RawData– 533 *CCD Linearity*

Outputs:

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

Required accuracy, constraints:

better than 1% on the photometric scale

TSF:

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

Needed functionality:

image - trim; mage - arithmetic; image - statistics

CA:

Assuming an input list of de-biased, shutter corrected dome flats with exposure times of 2, 60, 50, 4, 8, 40, 30, 1, 16, 24, 24, 16, 1, 30, 40, 8, 4, 50, 60 and 2 seconds, determine the mean value per flat, and plot as function of exposure time. Estimate the number of ADU's from where the plot becomes nonlinear.

Assuming that the CCD's are still linear with an exposure time of 40 seconds, divide the 40 second exposures by the 4 second exposures. 5σ outliers in the mean of this frame are pixels with an anomalous nonlinearity.

CAP:

input dome_list

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 20

```

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

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

non_linear_frame = (dome_list[6]/dome_list[4]+dome_list[14]/dome_list[4])

imstat = non_linear_frame.Stat()

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

output plot, non_linear_map

```

5.3.4 Req. — CCD Charge Transfer Efficiency

Inputs:

CalFile– 541 *Bias*

Outputs:

CalFile– 534 *charge transfer efficiency factors*

Required accuracy, constraints:

CTE > 0.999995 per parallel or serial shift.

TSF:

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

Needed functionality:

image – arithmetic; image – statistics

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 21

CA:

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

5.3.5 Req. — *CCD Cold Pixels*

Recipe:

Recipe– Dome_Flat or **Recipe– Twilight_Flat**

Inputs:

CalFile– 535 *Cold pixel map* previous version

CalFile– 546 *Master flatfield*

Outputs:

CalFile– 535 *Cold pixel map*

Required accuracy, constraints:

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

TSF:

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

Needed functionality:

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

CA:

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

NOVA - Kapteyn Institute USM - OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 22

CAP:

```
input flat_list, hot_map

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

output cold_map
```

5.3.6 Req. — *CCD Hysteresis, strong signal*

Recipe:

Recipe— Hysteresis

Outputs:

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

TSF:

Mode— stare N=2

TSF— OCM_img_obs_stare

Needed functionality:

catalog - associate; misc - plotting

CA:

Process the bright field as normal science data. Select the bright (saturated) objects from the catalog of the bright field. Use the pixel position of these sources to inspect the corresponding positions in the dark frame. Plot the source magnitude as function of time (exposure number), and measure the decay time.

If reminiscence is detected, repeat the experiment with more dark frames and determine decay-times.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 23

5.4.1 Req. — *Bias - doit*

Recipe:

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

Inputs:

Raw data bias frames

CalFile– 541 *Master Bias frame* previous versions
Laboratory values of bias levels.

Outputs:

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

Required accuracy, constraints:

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

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

TSF:

Mode– Stare N=10

TSF– OCM_img_cal_bias

Needed functionality:

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

CA:

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

Combine the trimmed images into an average bias frame, using 5σ rejection.

Compare mean of master bias frame with previous version.

Check whether mean level is in range.

CAP:

```
input bias_list, old_master_bias_stat
bias_list = bias_list.OverscanCorrection()
bias_list = bias_list.Trim()
master_bias = bias_list.Average(method='mean',
```

NOVA - Kapteyn Institute USM - OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 24

```

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

```

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

Recipe:

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

Inputs:

CalFile— 541 *Master Bias frame*

Outputs:

CalFile— 542 *Master Domeflat frame*

CalFile— 542L *Dome Lamp*

Required accuracy, constraints:

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

TSF:

Mode— Stare N=5

TSF— OCM_img_cal_domeflat

Needed functionality:

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

CA:

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

CAP:

input domeflat_list, bias

NOVA - Kapteyn Institute USM - OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 25

```

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

imstat = domeflat_list[0].Stat()

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

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

output master_domeflat, imstat

```

5.4.3 Req. — *Flat-field - twilight*

Recipe:

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

Inputs:

CalFile— 541 *Master Bias frame*

Outputs:

CalFile— 543 *Master Twilightflat frame*

Required accuracy, constraints:

Mean levels should be approximately 20000 ADU.

TSF:

Mode— Jitter N=5

TSF— OCM_img_cal_skyflat

Use an appropriate (empty) field, exposure time determined by tracker CCD,

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 26

or Tyson-Gal formula.

Needed functionality:

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

CA:

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

CAP:

```
input twilightflat_list, bias

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

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

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

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

output master_twilightflat, imstat
```

5.4.4 Req. — *Flat-field - night sky*

Recipe:

Recipe– Nightsky_Flat

Inputs:

CalFile– 541 *Master Bias frame*

NOVA - Kapteyn Institute USM - OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 27

CalFile– 542 *Dome flat* or **CalFile– 543** *Twilight flat*

Outputs:

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

Required accuracy, constraints:

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

TSF:

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

Needed functionality:

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

CA:

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

CAP:

```
input science_list, bias, flat
```

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

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

```
nightsky_flat = science_list.Average(method='mean',
```

NOVA - Kapteyn Institute USM - OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 28

```
reject_method='sigma', reject_level=3)
```

```
nightsky_flat = nightsky_flat*flat
```

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

```
output nightsky_flat, imstat
```

5.4.5 Req. — *Flat-field - Fringing*

Recipe:

Recipe— Fringe_Flat

Inputs:

The science observations themselves are used.

Outputs:

CalFile— 545 *ff-fringe*

TSF:

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

Needed functionality:

image - defringing

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

Recipe:

Recipe— Master_Flat

Inputs:

CalFile— 522 *Hot pixel map*

CalFile— 535 *Cold pixel map*

CalFile— 542 *Dome flat*

CalFile— 543 *Twilight flat*

CalFile— 544 *Night Sky flat*

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 29

CalFile– 548 *Illumination Correction*

Outputs:

CalFile– 546 *Master flatfield*

CalFile– 546W *Master weight map*

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

Needed functionality:

image - masking; image - arithmetic

CA:

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

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

CAP:

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

output weight_image
```

5.4.7 Req. — Quick detector responsivity check - doit

Recipe:

Recipe– Quick_Checkalso run on-site

Inputs:

CalFile– 542L *Dome Lamp*

CalFile– 547 *Quick check* older versions

Outputs:

CalFile– 547 *Quick check*

NOVA - Kapteyn Institute USM - OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 30

CalFile– 547r *Quick check -day report*

Required accuracy, constraints:

1%

TSF:

Mode– Stare N=1

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

= **TSF– OCM_img_cal_quick**

Needed functionality:

image - trim; image - arithmetic; image - statistics

CA:

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

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

5.4.8 Req. — *Illumination correction*

Recipe:

Recipe– Illumination_Correction

Inputs:

CalFile– 546 *Master flatfield*, build with a uniform illumination correction

CalFile– 569 *Secondary Standards*

RawData– 563 *Zeropoint - Keyband* or **RawData– 564** *Zeropoint - Userband*

Outputs:

CalFile– 548 *Illumination correction*

Required accuracy, constraints:

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

CA:

Fit the deviation of the measured Zeropoint of individual standards from

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 31

a uniform Zeropoint for the whole field with a polynomial modelling the illumination correction of the field of each individual Chip.

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

Inputs:

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

Outputs:

CalFile– 551 *Astrometric camera/chip solution*

Required accuracy, constraints:

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

TSF:

Mode– dither N=5

TSF– OCM_img_obs_dither, each filter, ADC In/Out

CA:

Data is reduced as standard science data, but co-addition is not required.

SeqFile– 634C *Astrometrically calibrated catalogue* produced by the standard pipeline contains the relative positions of all the chips. Print offsets etc in **SeqFile– 634C** *Astrometrically calibrated catalogue* and compare with focal plane design values (previous versions of 634C).

5.5.2 Req. — *Telescope Pointing*

Inputs:

Offset Guide CCD

Outputs:

Conformance flag.

Required accuracy, constraints:

1 arc second

TSF:

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

CA:

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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 32

5.5.3 Req. — *Telescope and Field Rotator tracking*

Outputs:

Conformance flags Source extraction files
Source extraction calfiles (configuration, parameters files)

Required accuracy, constraints:

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

Needed functionality:

catalog - PSF fitting; misc - regression

CA:

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

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

CAP:

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

Later trend analysis if present. This is a pure database type of operation. For a given period in time, defined by the instrument/telescope configuration and the pointing model version functional dependencies of astrometric calibration

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 33

parameter describing the plate rotation with Alt en Az are derived. Whenever a functional dependence exceeds the specified positional accuracy a non-conformance flag is produced.

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

5.5.4 Req. — *PSF Anisotropy*

Recipe:

Recipe— PSF_anisotropy

Inputs:

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

Outputs:

CalFile— 554 *PSF anisotropy*

Required accuracy, constraints:

better than 1%

TSF:

Mode— Stare N=1

TSF— OCM_img_obs_stare

Needed functionality:

catalog - PSF fitting with Kaiser method

CA:

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

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

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

Inputs:

Reference position catalog (see A4)

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 34

Outputs:

CalFile– 556 *Guide CCD guide star signal and offset*

astrometry solutions inserted into the descriptors; handed over manually to instrument S/W responsible

Required accuracy, constraints:

1 arcsec rms for the accuracy with respect to the external standard;
External precision is driven by the position reference catalog. This is in the case of the USNO-A2 catalog of the order 0.3" with possible systematic excursions to 1".

Needed functionality:

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

CA:

Description of calibration analysis (also mathematical, error propagation)

See req.5.5.5.

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

CAP:

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

5.6.1 Req. — Shutter Timing

Recipe:

Recipe– Shutter_Delay

Inputs:

CalFile– 541 *Bias*

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 35

Required accuracy, constraints:

Timing error less than 0.2%.

TSF:

Mode– Stare $N=4$

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

= **TSF– OCM_img_cal_shutter**

Needed functionality:

image – collapse;

CA:

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

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

CAP:

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

```
line = tmp.collapse()
```

```
output line
```

5.6.2 Req. — Photometric Calibration - monitoring

Recipe:

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

Inputs:

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

CalFile– 563Z *Zeropoint - extinction - keybands* of that night ($g_{st.e}(X) \times g_e(0)$)

CalFile– 562S *Sky brightness* Reference values

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 36

CalFile– 569 *Standard Catalog*

CalFile– 541 *Master Bias Frame*

CalFile– 546 *Weightmap*

Outputs:

CalFile– 562 *Extinction - night report ($g_e(t) \times g_{st.e}(X) \times g_e(0)$ at various t*

CalFile– 562u *Photom-u' Stars + Sky*

CalFile– 562B *Photom-B Stars + Sky*

CalFile– 562V *Photom-V Stars + Sky*

CalFile– 562i *Photom-i' Stars + Sky*

Series of output files will be used for trend analysis

Required accuracy, constraints:

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

TSF:

Strategy– freq

Mode– Stare N=1

(**TSF– OCM_img_obs_stare,N=1, filter=composite**)

= **TSF– OCM_img_obs_monit**

Needed functionality:

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

CA:

Dependency: **req.563** for that night should be determined first.

Run standard image pipeline first: i) subtract bias ii) divide flat field iii) import zeropoint calfile.

- run **Sextractor** to obtain catalog

- obtain astrometric solution

- identify standards in astrometrically calibrated catalog to obtain star magnitudes + sky brightness (stellar photometry not used anywhere else in present set-up)

- compare star magnitudes with star magnitudes adopted **req.563** to generate OK flags and night report

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 37

- import **CalFile– 563Z** *Zeropoint - extinction - key bands* of that night
 - obtain extinction values and time stamp for part of night-night report.
- Long term trend analysis is done on **CalFile– 562u, B, V and i** which are obtained every night 3 times.
- Make “lightcurve” of each standard star in the field
 - report and plot all stars with deviations larger than 3σ .
- For the fast recipe of the health check, the following steps will be performed.
- Determine the position in each CCD for the objects from the input catalog
 - Extract a 32 by 32 pixel region centered at each position.
 - Find the local maximum within the region.
 - Determine background in the the region, and subtract this.
 - Compute first and second order moments of the signal around the maximum
 - Compare measurements with values from the input catalog.

5.6.3 Req. — *Photometric Calibration - zeropoint key bands -doit*

Recipe:

Recipe– PhotCal_Extract_Zeropoint

Inputs:

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

External magnitudes:

CalFile– 569 *Standard Catalog*

For each night:

CalFile– 562 *Extinction night report* **CalFile– 564E** *Standard extinction curve*

Outputs:

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

Required accuracy, constraints:

1% on the photometric scale

TSF:

Strategy– freq

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 38

Mode– Stare N=1

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

= **TSF– OCM_img_obs_zpkey**

Needed functionality:

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

CA:

The solution has to solve the following “gains”:

$g_{ext}(X)$ = gain = atmospheric extinction for unit airmass

$g_{DQE}(N, X)$ = gain = DQE of individual chip N in pass band X

(Latitude Paranal is $-24^{\circ}37'$, Polar field ZD = $\sim 65^{\circ}$ airmass is 2.40, equatorial field (ZD = $\sim 24^{\circ}$ airmass is around 1.10).

The u' , B,V and i' images on equatorial fields provide for each of the 32 chips the values of $I_{obs,X}(N)/I_{ref,X}$ in the equations:

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

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

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

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

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

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

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

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

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

Now consider the 8 chips which are common in the first and second set of measurements in the pass band B:

one can solve $g_{DQE}(0, N = 1...8, u')$ and 8 times $g_{ext}(0, u') \times g_{st.e}(B)$.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 39

Idem dito for the other passbands we obtain:

$g_{DQE}(0, N = 9...16, B)$ and 8 times $g_{ext}(0, B) \times g_{st.e}(B)$.

$g_{DQE}(0, N = 17...24, V)$ and 8 times $g_{ext}(0, V) \times g_{st.e}(V)$

$g_{DQE}(0, N = 25...32, i')$ and 8 times $g_{ext}(0, i') \times g_{st.e}(i')$.

Next, these intermediate results (8 times $g_{ext}(0, u')$, $g_{ext}(0, B)$, $g_{ext}(0, V)$ and $g_{ext}(0, i')$) are determined relative to the standard extinction curve (**CalFile-564E**); this is used as a quality check, which also provides the accuracy of the measured extinction. There is quite a number of exceptional situations the code has to be able to deal with, like one chip outlying, one passband outlying etc etc. Perhaps, the safest mode of automatic processing is, after the filtering of the outliers in the measurements of $g_{ext}(0, X)$, to determine the overall shift of the standard extinction curve (which is actually a gain $g_{ext}(0)$) using the remaining of the 64 measurements ($64 = 2 \times 8 \times 4 = (\text{eq+polar}) \times N \times X$). (yes indeed, using the fourshooter once on the equatorial field, once on the polar fields results into 64 measurements of the extinction !!)

This number can then be substituted in the above list of equations to obtain $g_{DQE}(0, N, X)$ for each chip N and each band X . Actually these numbers will be derived three times, and this can be used in the error estimate and quality check.

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

Recipe:

Recipe– PhotCal_Extract_Zeropoint

Inputs:

Reference magnitudes and transformations:

CalFile– 569 *Standard Catalog*

CalFile– 565 *User -> key*

CalFile– 564E *Standard extinction curve*

Each night:

CalFile– 562 *Extinction night report*

Outputs:

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

NOVA - Kapteyn Institute USM - OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 40

Required accuracy, constraints:

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

TSF:

Mode– Stare N=1

(**TSF**– OCM_img_obs_stare, N=1, filter=userband)

= **TSF**– OCM_img_obs_zpuser

Needed functionality:

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

CA:

See req.563 for CA.

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

Inputs:

Reference magnitudes and transformations:

CalFile– 569 *Standard Catalog* **CalFile**– 564E *Standard extinction curve*

each night:

CalFile– 562 *Extinction night report*

Outputs:

CalFile– 565 *User -> key*

Required accuracy, constraints:

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

5.6.6 Req. — *Dependency on rotator angle/reproducibility*

Outputs:

Flat fields - internal

Required accuracy, constraints:

1% on the photometric scale

TSF:

Mode– Stare N=12

TSF– OCM_img_cal_domeflat

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 41

and

Mode– Stare N=12

TSF– OCM_img_obs_stare

CA:

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

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

Outputs:

OK flag

Required accuracy, constraints:

Better than 1% on the photometric scale

TSF:

Mode– Stare N=2

TSF– OCM_img_obs_stare

and

Mode– jitter N=5

TSF– OCM_img_obs_jitter

and

Mode– dither N=5

TSF– OCM_img_obs_dither

CA:

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

5.6.8 Req. — *Detection limit and ETC calibrations*

Outputs:

Values for ETC

Required accuracy, constraints:

10 % in detection limit

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 42

CA:

Interactive analysis

5.6.9 Req. — *Secondary Standards*

Recipe:

Recipe– Secondary_Standards

Inputs:

CalFile– 569E *Primary Standard stars*

Outputs:

CalFile– 569 *Standard Catalog*

Required accuracy, constraints:

0.02 mag in individual secondary standards stars.

TSF:

Strategy– mosaic

Mode– Stare N=32

TSF– OCM_img_obs_stare

Needed functionality:

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

CA:

Reduce each CCD separately, using the zeropoint and illumination correction of the observation containing the primary standards to do the photometric calibration. Extract a catalog of photometrically calibrated stars with photometric errors < 0.03 mag for each CCD. This will result in 32 catalogs per CCD of candidate secondary standard stars, for a total of 1024 catalogs. Candidate secondary stars in the central square degree of these observations will have been observed at least 8 times (with different CCDs), while those at the corners of the 2 by 2 degree area that has been covered, have been observed only once. Select the candidate secondary standards with at least 7 different observations, and average these to obtain a catalog of secondary standards with 0.02 mag accuracy per standard over approximately 1.2 square degree area.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 43

5.7.1 Req. — *Camera focus/tilt*

Recipe:

Recipe– FocusStandard Paranal focus MIDAS procedure

Outputs:

focus offset values to be transferred to INS data base

Conformance flag for optical thickness of all filters.

Conformance flag for tilt

TSF:

TSF– OCM_img_tec_focuseq

CA:

This is an on-line activity which is performed using a RTD/MIDAS procedure.

Resulting plots are used to determine and verify the camera focus.

Additional data reduction for tilt TBD; Make matrix of PSFs. For each star determine at which M2 setting image is the sharpest; produce a 2 dim-image map of M2 settings with optimal focus.

5.7.2 Req. — *Ghosts - ADC*

Required accuracy, constraints:

TSF:

Mode– Stare N=1

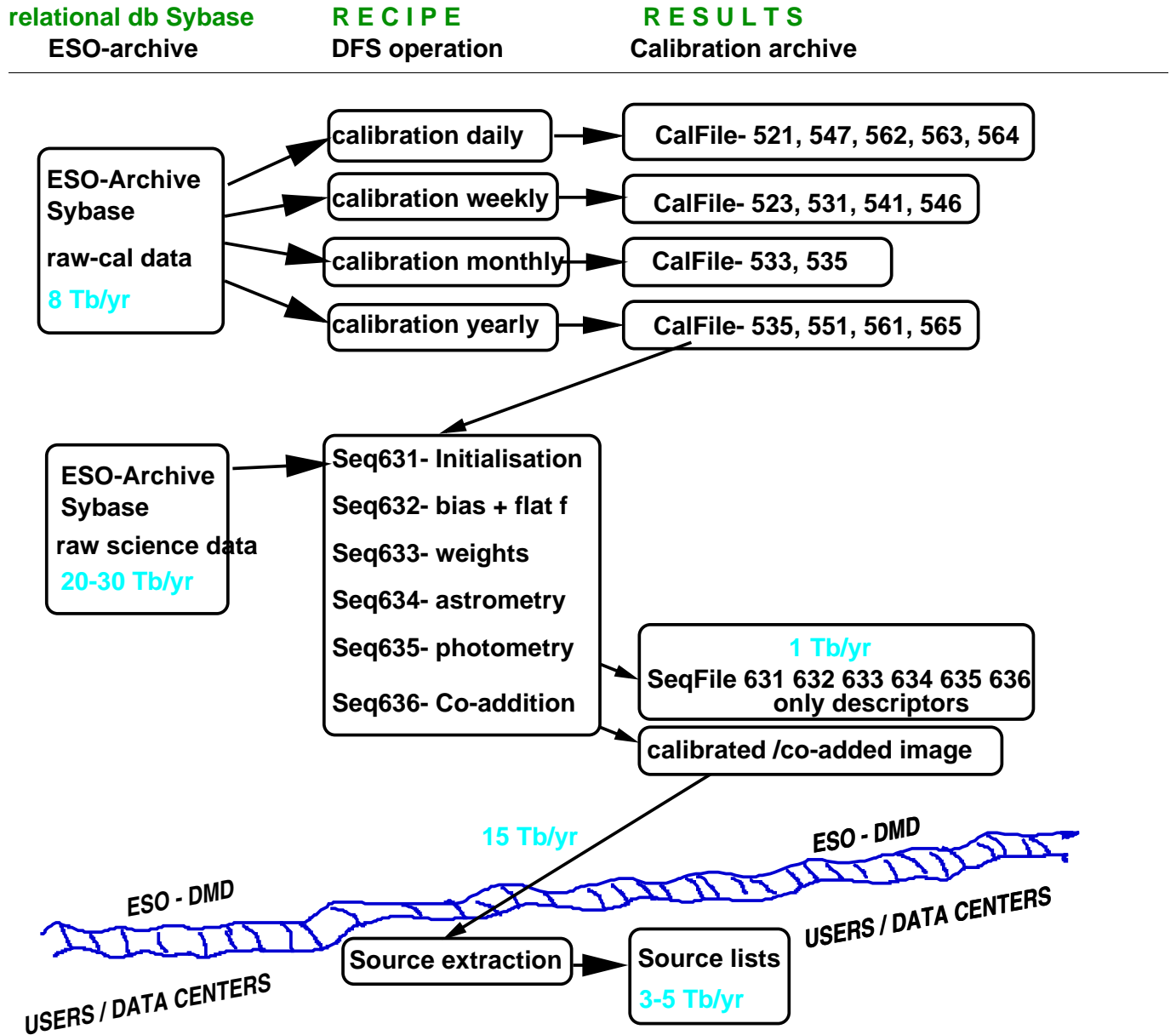
TSF– OCM_img_obs_stare

CA:

Standard image pipeline, visual inspection of images

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 44

Fig 6. Data Flow of Science and Calibration data



NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 45

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).

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 46

- **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 successfully. 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 Quality 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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 47

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–** sare 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 analysis 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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 48

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 telescope 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"

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 49

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.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 50

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:

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 51

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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1
		Date 29 Oct 2001
		Page 52

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.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 53

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).

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 54

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**

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 55

ASTRONOMICAL SOURCE LIST DATA VOLUME

NOMINAL USING CO-ADDED FRAMES

25 sources per square arcmin $\rightarrow 10^5$ sources/degree²
(CFHT reckons 2×10^5 for 4m telesc. $4^2/2.5^2 = 2.5$)

20 - 30 parameters per source $\rightarrow 2-3 \times 10^6$ real*4/degree² = 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 $10 \times 8.3 \times 5 = 0.4$ Tb of source data on non co-added frames

few observing runs end up in Tb regime

6.3 Specifications of 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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 56

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**

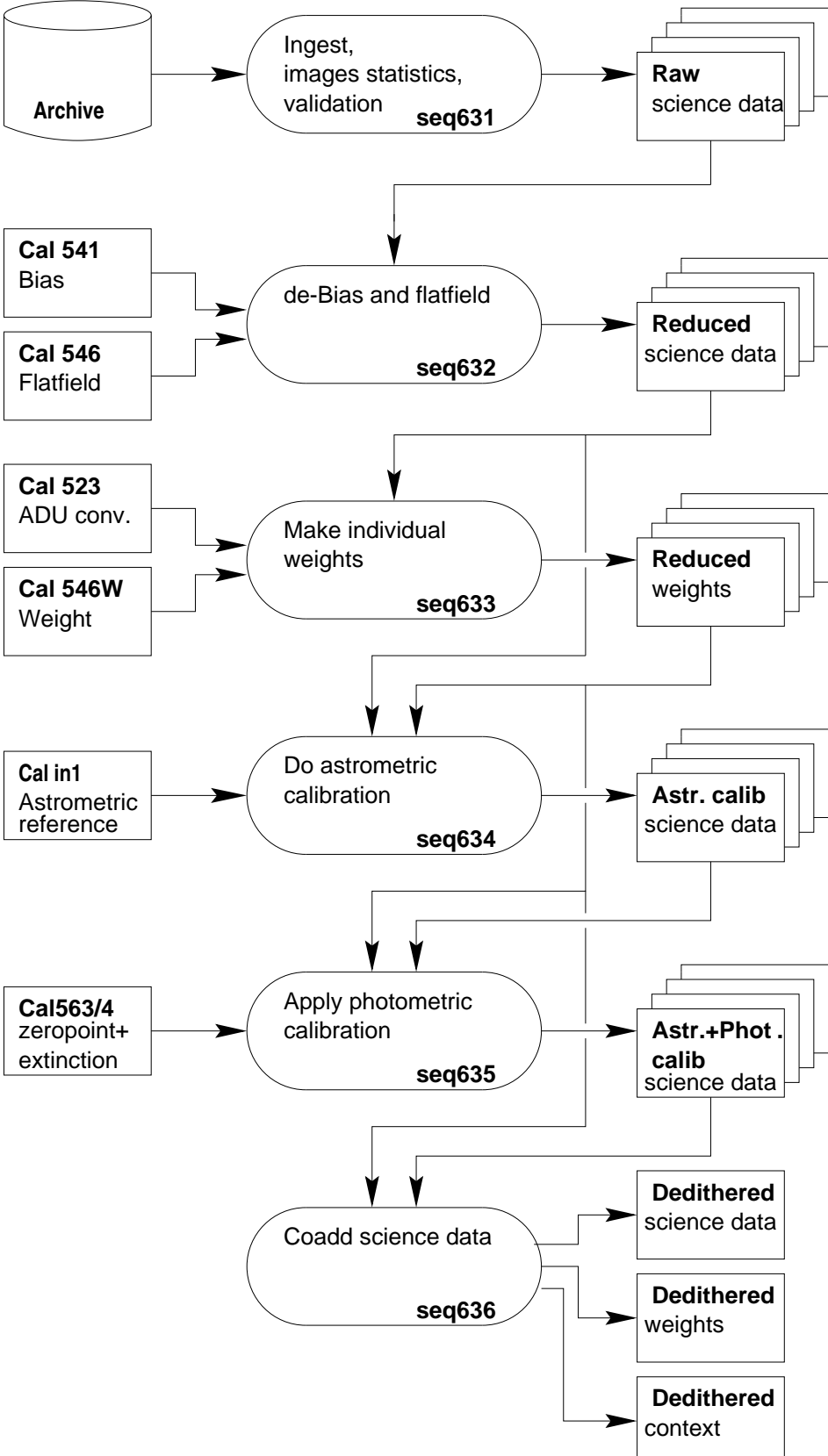
The recipes (Science_Stare, Science_Jitter, Science_Dither) combine a series of processing steps that are specified by their (intermediate) data product in **seq.– 631–seq.– 636**. These can be summarized by:

- **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.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1
		Date 29 Oct 2001
		Page 57

Image pipeline dataflow



NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 58

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 information.

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

6.3.1 **Seq.** — *Initialization and image statistics*

Objective:

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

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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 59

Presently, image data arrive from the telescope in the form of FITS files with the data for each chip stored into a single FITS extension. For the purpose of efficient parallel processing this **seq.-** splits the FITS files (and their extensions) into individual FITS files for individual chips. In the future this functionality may be provided generically by the pipeline environment

It is assumed that incoming raw data are valid FITS files. Further qualification of the raw data by means of image statistics and a preliminary measurement of the seeing (TBC), should determine whether the data can be meaningfully processed by the pipeline.

If the image pipeline uses a local database then the first step in pipeline processing is the ingestion of the raw data into the database. Upon ingestion the image headers are translated into database descriptors. In addition, the Quality Control Parameters (image statistics and seeing) are added to the image descriptor in the database.

Inputs:

Raw science frames.

Outputs:

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

Estimated time needed:

TBD

Needed functionality:

image - statistics

CAP:

input image

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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 60

```
image.Ingest()
```

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

Objective:

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

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

Inputs:

SeqFile– 631 *Raw science frame*

CalFile– 541 *Bias*

CalFile– 546 *Master Flatfield*

Outputs:

SeqFile– 632 *Reduced science frame*

Updated image statistics

Estimated time needed:

Approximately 30 seconds/CCD

Needed functionality:

image - trim; image - statistics

CAP:

```
input image, bias, flat
```

```
image = image.OverscanCorrection()
```

```
image = image.Trim()
```

```
image = (image-bias)/flat
```

```
image_stats = image.stat()
```

```
output image
```

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 61

6.3.3 Seq. — *Construct individual weights*

Objective:

Construct individual weight maps.

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

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

Inputs:

SeqFile– 632 *Reduced science frame*

CalFile– 546W *Master weight image*

Outputs:

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

Estimated time needed:

Approximately 3 min/CCD

Needed functionality:

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

CAP:

`input image, master_weight`

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

```
    check_image=SEGMENTATION)
```

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 62

```

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

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

sattelite_mask = catalog.FindSatelliteTracks()

weight = master_weight*(1-sattelite_mask)

output weight

```

6.3.4 Seq. — *Astrometric calibration*

Objective:

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

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

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

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

The default astrometric solution is obtained on a 'per chip' basis. Alternatively, one can choose to use the overlap that results from a repeated observation of the same area of sky in a jittered or dithered observation to

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 63

improve on this solution. Improved accuracy is obtained if one uses the overlap information for a single chip. Maximum accuracy is obtained if one also uses the overlap between different chips in dithered observations. The latter method breaks the inherent parallelism of processing individual chips.

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

The astrometrically calibrated image is used when building the dedithered image (**seq.- 636**)

Inputs:

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

Outputs:

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

Estimated time needed:

Approximately 1 min/CCD

Needed functionality:

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

CA:

First **sextractor** is used to obtain an image catalog. The catalog is used to obtain an astrometric solution. The solution is added to the header of the background subtracted image.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 64

Optionally the catalog can be combined with catalogs of subsequent observations of the same area with the same chip and observations of the same area with other chips.

The catalog can also be used to characterize the seeing.

Note that the sextractor run can be combined with the sextractor run of **seq.- 633**.

CAP:

```
input image, weight, seeing, reference_catalog

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

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

output ast_image, ast_catalog, image_stats
```

6.3.5 Seq. — *Apply photometric calibration*

Objective:

Apply photometric calibration.

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

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

Inputs:

SeqFile- 634 *Astrometrically calibrated science image*

CalFile- 563 *Zeropoint and extinction - keybands, or*

CalFile- 564 *Zeropoint and extinction - userbands*

Outputs:

SeqFile- 634 *Astrometrically calibrated science image zeropoint added*

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 65

Estimated time needed:

negligable

CA:

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

CAP:

```
input image, zeropoint, extinction
```

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

```
output image
```

6.3.6 Seq. — *Co-addition*

Objective:

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

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

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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 66

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

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

Prior to coaddition a background subtraction step shall be performed.

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

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

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

Swarp is a package specifically designed to handle these operations.

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

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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 67

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

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

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

Inputs:

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

SeqFile– 633 *Individual weight images*

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

Outputs:

SeqFile– 636 *Dedithered image* including statistics and seeing

SeqFile– 636W *Dedithered weight_image*

SeqFile– 636C *Context image, including context table*

SeqFile– 636cat *Catalog*

sensitivity description

Estimated time needed:

TBD

Needed functionality:

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

CA:

Call **OmegaCAM** version of **swarp** with the input data as parameters. De-

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051 Issue VERSION 1.1
	DRS	Date 29 Oct 2001 Page 68

termine statistics of output image. Run **sextractor** on the output image. Determine the PSF variation over the FOV from the resulting catalog, and compare this to the seeing of the input images (determined in **seq. 634**).

CAP:

```
input image_list, weight_list, reference_coordinate_system
```

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

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

```
output dedithered_image, dedithered_weight, context_map
```

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 69

7 NEEDED FUNCTIONALITIES

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

7.1 Image manipulation

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

image arithmetic

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

This functionality is provided by **eclipse**.

image statistics

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

This functionality is provided by **eclipse**.

trimming and overscan correction

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

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

This functionality is provided by **eclipse**.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 70

averaging

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

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

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

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

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

This functionality is provided by **eclipse**.

masking

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

This functionality is provided by **eclipse**.

satellite detection

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

cosmic ray detection

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

collapse

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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 71

background subtraction

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

coaddition

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

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

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

Once all input images and their weights have been resampled onto the grid specified by the coordinate system of the coadded image, it is straightforward to compute the coadded image and its weight. Given resampled input images $1 \leq i \leq N$ entering co-addition, one can define for each pixel j :

- the local uncalibrated flux $f_{ij} = \overline{f_{ij}} + \Delta f_{ij}$, where $\overline{f_{ij}}$ is the sky background, and Δf_{ij} the contribution from celestial sources,
- the local uncalibrated variance $\sigma_{ij}^2 = \overline{\sigma_{ij}^2} + \Delta \sigma_{ij}^2$, where $\overline{\sigma_{ij}^2}$ is background noise and $\Delta \sigma_{ij}^2$ the photon shot noise of celestial sources,
- the local, normalized weight w_{ij} ,
- the electronic gain of the CCD g_i ,
- the relative flux scaling factor p_i , deduced from the photometric solution, with $p_i \Delta f_{ij} = p_l \Delta f_{lj}$ for all i, l, j ,
- the weight scaling factor k_i .

Optimal weighting is obtained using

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 72

$$k_i w_{ij} = \frac{1}{p_i^2 \sigma_{ij}^2},$$

leading to a co-added flux (assuming the background of the input images has been subtracted),

$$f_j = \frac{\sum_i k_i w_{ij} p_i \Delta f_{ij}}{\sum_i k_i w_{ij}},$$

and variance

$$\sigma_j^2 = \frac{\sum_i k_i^2 w_{ij}^2 p_i^2 \sigma_{ij}^2}{(\sum_i k_i w_{ij})^2},$$

The software package **Swarp**, developed by E. Bertin (IAP) for Terapix provides a set of regridding and co-addition algorithms specifically optimized to handle large area CCD mosaics

7.2 Catalog manipulation

Several reduction steps, in particular astrometric and photometric calibration, require the manipulation of source lists/catalogs. Most of this functionality is provided by the Leiden Data Analysis Center (**LDAC**) data reduction tools.

source extraction

The detection and measurement of sources in images is a non-trivial task. Fortunately an established, versatile, robust and fast algorithm for the detection of sources is available in the form of the **SExtractor** source extraction package. In addition to its source detection capabilities **SExtractor** provides functionality for the detection of image defects (cosmic rays and bleeding), and for robust background subtraction in the presence of signal.

association

Both astrometric and photometric calibration require the association of a source catalog with a reference catalog. A proper association algorithm takes into account position errors and confusion problems.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 73

Catalog association is provided by **LDAC**.

merge

In some cases it may be necessary to merge overlapping catalogues into a new catalogue, containing a suitable average of the different measurement of a single object in different observations.

Catalog merging is provided by **LDAC**.

astrometric solution

The astrometric solution performs, based on the a-priori pointing knowledge of the telescope and the chip layout, a pattern matching between the extracted observed objects and a reference catalog allowing quick, inaccurate pairing. To increase the reliability of the initial pairing, previous determinations of the full astrometric solution are used as a first step approximation.

Using this pairing information the parameters of the astrometric model are derived in an iterative process. The full astrometric solutions determine both the projection of the individual chip pixel coordinates onto the perfect (x,y) coordinate space of the focal plane and the projection of this perfect plane to sky coordinates. This effectively maps the light path through the telescope and the camera for the particular pointing from the pixel plane to the sky coordinate domain. If multiple pointings are available (as is the case in **Mode-dither N=** or **Mode-jitter N=**) different pixels and/or detectors map the same sky area. The source extraction precision in arcseconds is much higher than the positional accuracy of the reference catalog. Incorporating the overlap information therefore enhances the accuracy of the final astrometric solution to allow more precise co-addition.

The astrometric solution can be derived in several ways of increasing complexity and potentially increasing accuracy. Single chip solutions where the astrometric solution for each CCD chip is derived independently is the simplest and least accurate. When multiple pointings on the same area of sky are performed close in time, for each CCD chip one will have multiply observed the set of reference stars and one can also use non-reference stars observed multiple times among the pointing series. Still an astrometric solution per chip is derived, which is more accurate than the single chip, single pointing case. The most robust way of determining an astrometric solution of a multi CCD camera is to make use

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 74

of the dithering pattern which creates not only overlaps of one CCD chip onto itself, but also among the different chips of the camera. Now a full astrometric solution can be derived for all chips simultaneously using all overlap cases (chips onto themselves, between different chips). Obviously this can produce the most accurate astrometric solution of the three.

As is customary, the plate model is not defined as a mapping between pixel coordinates and sky coordinates (α, δ) , as this would obviously have singularities at the poles, but instead as a mapping between the pixel space and so-called normal coordinates. The normal coordinates (ζ, η) are the gnomonic projection of the absolute sky positions relative to the field center. There is some level of non-linearity here, since the field center itself depends on the position reconstruction, but for realistic initial errors this is very small and easily absorbed in the plate model. With these notations, the mapping between a source detected at pixel coordinates (x, y) in frame f and its normal coordinates (ζ, η) relative to the nominal center of field f is of the form

$$\zeta(x, y, f) = a_f + \sum_{i+j=1}^{i+j=p} \sum_{k=0}^n b_{ijk} x^i y^j f^k$$

$$\eta(x, y, f) = c_f + \sum_{i+j=1}^{i+j=p} \sum_{k=0}^n d_{ijk} x^i y^j f^k$$

where the a_f , c_f , b_{ijk} , and d_{ijk} are initially unknown coefficients, to be determined by the least squares adjustment. We actually use a different maximum degree in the field number variable for each spatial term, since flexures only induce measurable effects for the low order terms (zero point and focal scale).

astrometric solution – Overlap solution

Upon closer examination, the star density of the reference catalog is indeed almost always sufficient. One does, however, gain accuracy by incorporating the better positional accuracy within the chips of a detector than that with respect to an external reference frame. Giving overlap position determinations higher weight than those with respect to the external reference system one enhances positional accuracy.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 75

The coefficients of the plate model will thus be determined by simultaneously minimizing (in a least square sense) the distance to the reference stars and the overlap detections. The corresponding quadratic form can be written as:

$$\begin{aligned}
S = & \sum_{f=1}^{n_{field}} \sum_{i=1}^{n_{ref}^f} \frac{\left\| \zeta(x_i, y_i, f) - \zeta_i^f \right\|^2}{\sigma_{mes}^2(i) + \sigma_{cat}^2(i)} + \sum_{f=1}^{n_{field}} \sum_{i=1}^{n_{ref}^f} \frac{\left\| \eta(x_i, y_i, f) - \eta_i^f \right\|^2}{\sigma_{mes}^2(i) + \sigma_{cat}^2(i)} \\
& + \sum_{f_1=1}^{n_{field}} \sum_{f_2=1}^{n_{field}} \sum_{i=1}^{n_{over}^{f_1 f_2}} \frac{\left\| (\zeta(x_i, y_i, f_1) - \zeta(x_i, y_i, f_2)) - (\zeta_i^{f_1} - \zeta_i^{f_2}) \right\|^2}{\sigma_{mes}^2(i, f_1) + \sigma_{mes}^2(i, f_2)} \\
& + \sum_{f_1=1}^{n_{field}} \sum_{f_2=1}^{n_{field}} \sum_{i=1}^{n_{over}^{f_1 f_2}} \frac{\left\| (\eta(x_i, y_i, f_1) - \eta(x_i, y_i, f_2)) - (\eta_i^{f_1} - \eta_i^{f_2}) \right\|^2}{\sigma_{mes}^2(i, f_1) + \sigma_{mes}^2(i, f_2)}
\end{aligned}$$

where ζ and η are the multivariate polynomial functions described above, ζ_i^f and η_i^f are the normal coordinates of reference star i relative to the center of field f , and $(\zeta_i^{f_1} - \zeta_i^{f_2})$ and $(\eta_i^{f_1} - \eta_i^{f_2})$ are the difference of the normal coordinates of overlap star i relative to the centers of fields f_1 and f_2 . In principle, the latter quantities can only be evaluated once the coordinates are at least approximately known, but in practice they only vary by a few milliarcseconds across the overlap zone. One can also note that the solutions for ζ and η are not coupled, and that one thus independently minimizes S_ζ and S_η , the parts of S depending on respectively ζ and η .

Astrometric solution – Implementation

We consider here an ensemble of n_f fields containing a total of N_{ref} reference stars and N_{over} stars in overlaps, and adjust a plate model which has n_{par} smoothly varying functions (such as the polynomials discussed above) with coefficients noted as b_p , plus one zero point per field noted as b_f .

For a practical discussion of the implementation, it is convenient to rewrite the quadratic form of the above equation in its canonical form

$$S = (A \cdot X - B)^T \cdot (A \cdot X - B)$$

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 76

where A is a rectangular matrix (the design matrix) whose dimensions are the total number of constraints (reference+overlap) and the total number of fitted coefficients (field centers+smooth functions). X and B are vectors containing respectively the fitted coefficients and the constraints data. If one defines X , B , and A by respectively

$$X_i = a_f \text{ for } i \leq n_f$$

$$X_i = b_p \text{ for } i > n_f$$

$$B_i = \zeta_{i f_i} \text{ for } i \leq N_{ref}$$

$$B_i = (\zeta_{i f_i^1} - \zeta_{i f_i^2}) \text{ for } i > N_{ref}$$

$$A_{ij} = \delta_{j f_i} / \sigma_i \text{ for } i \leq N_{ref} \text{ and } j \leq n_f$$

$$A_{ij} = f(x_i, y_i, f_i) / \sigma_i \text{ for } i \leq N_{ref} \text{ and } j > n_f$$

$$A_{ij} = (+\delta_{j f_i^1} - \delta_{j f_i^2}) / \sigma_i \text{ for } i > N_{ref} \text{ and } j \leq n_f$$

$$A_{ij} = (f(x_i, y_i, f_i^1) - f(x_i, y_i, f_i^2)) / \sigma_i \text{ for } i > N_{ref} \text{ and } j > n_f$$

where δ_{ij} is as usual a Kronecker symbol. A similar formulation obviously exists for η .

Under this canonical formulation of the least square quadratic form, it is easy to show (see for instance the least square chapter in Numerical Recipes) that the X which minimizes S is the solution of the system of $(n_{par} + n_f)$ linear equations $(A^T \cdot A) \cdot X = A^T B$, known as the normal equations.

The plate model coefficients can thus be obtained by computing $(A^T \cdot A)$ and solving the normal equations. This method is generally known to have relatively poor numerical stability. Once the pixel coordinates are remapped to $[0,1]$ however, the problem has good conditioning, and direct comparison with more accurate methods shows good agreement for modest polynomial degrees, even in single precision. Alternatively, A is sparse enough that solving the equation with the conjugate gradient algorithm is a possibility. This iterative minimization algorithm converges in at most $n_{par} + n_f$ steps, each of which needs one multiplication by A and its transpose. It has good stability, is about as fast as computing $(A^T \cdot A)$, but needs a larger memory space.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 77

If on the other hand an analytic estimate of the standard errors is needed, $(A^T \cdot A)^{-1}$ (which is the covariance matrix) must be evaluated anyway. Solving the normal equations then becomes much cheaper, though we may still use the conjugate gradient for the minimization, because of its better numerical behaviour.

The complete implementation of these algorithms is provided by **LDAC**

PSF fitting

Use the second order moments of the brightness distribution of stellar objects to search for systematic effects across the detector area. The distribution of the position angles and elongations of the bounding ellipse has to be evaluated. A robust method for determining these parameters comes from Kaiser et al. 1995, APJ 449, 460. Alternatively use the PSF fitting functionality from **sextractor**

seeing

The seeing is robustly characterized by the half light radius r_e of unsaturated stellar objects, obtained from **sextractor**

select stars

Star galaxy separation is functionality provided by **sextractor**

7.3 Header manipulation

Header manipulation, i.e.: reading and writing and modifying (representations of) FITS headers, constitutes basic functionality, provided by many astronomical data reduction packages. Missing from most header manipulation software however are validation tools. We also note that it is nowhere specified in what order header keywords are written, while some sort of fixed order would greatly improve human readability of FITS headers.

reading

Header reading includes copying of the FITS header in some kind of internal representation, as well as the extraction of values for a particular keyword from a given header.

writing

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 78

Header writing includes writing a FITS header based on some internal representation, as well as writing a value for a particular keyword in a given header. Header writing should conform to the formatting directives given by a Data Interface Dictionary.

validation

Header validation should be based on Data Interface Dictionaries. There are currently no tools that verify existing FITS headers against Data Interface Dictionaries. The Fits Translation Utility (FTU) only validates new header items written by this tool.

7.4 Miscellaneous functionalities

Miscellaneous functionalities required for **OmegaCAM** data reduction include:

regression/(non-)linear fitting

Some results (zeropoints, gains) are obtained from fits to multi dimensional data.

plotting

Simple x-y scatter plots can provide useful graphical representations of results.

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 79

A1 LIST of CALIBRATION REQUIREMENTS

- 5.2.1 Req.– *CCD read noise - doit* 13
- 5.2.2 Req.– *hot pixels*..... 14
- 5.2.3 Req.– *CCD gain* 15
- 5.2.4 Req.– *Electromagnetic Compatibility*..... 16
- 5.2.5 Req.– *Electrical cross talk*..... 17
- 5.3.1 Req.– *CCD Dark Current - doit*..... 17
- 5.3.2 Req.– *CCD Particle Event Rate*..... 18
- 5.3.3 Req.– *CCD Linearity*..... 19
- 5.3.4 Req.– *CCD Charge Transfer Efficiency*..... 20
- 5.3.5 Req.– *CCD Cold Pixels* 21
- 5.3.6 Req.– *CCD Hysteresis, strong signal*..... 22
- 5.4.1 Req.– *Bias - doit*..... 22
- 5.4.2 Req.– *Flat-field - dome key bands + user bands - doit*..... 24
- 5.4.3 Req.– *Flat-field - twilight*..... 25
- 5.4.4 Req.– *Flat-field - night sky* 26
- 5.4.5 Req.– *Flat-field - Fringing*..... 28
- 5.4.6 Req.– *Flat-field - master flat and weight map* 28
- 5.4.7 Req.– *Quick detector responsivity check - doit*..... 29
- 5.4.8 Req.– *Illumination correction*..... 30
- 5.5.1 Req.– *Position of Camera in focal plane* 31
- 5.5.2 Req.– *Telescope Pointing*..... 31
- 5.5.3 Req.– *Telescope and Field Rotator tracking* 31
- 5.5.4 Req.– *PSF Anisotropy* 33
- 5.5.5 Req.– *The astrometric solution for templates - see 6.3.4* 33
- 5.5.6 Req.– *The astrometric solution for Guide CCD's* 33
- 5.6.1 Req.– *Shutter Timing*..... 34
- 5.6.2 Req.– *Photometric Calibration - monitoring* 35
- 5.6.3 Req.– *Photometric Calibration - zeropoint key bands -doit* .. 37
- 5.6.4 Req.– *Photometric Calibration - zeropoint user bands*..... 39
- 5.6.5 Req.– *Filter band passes - user bands vs key bands*..... 40
- 5.6.6 Req.– *Dependency on rotator angle/reproducibility*..... 40

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 80

5.6.7 Req.- *Linearity (as a function of flux)*..... 41

5.6.8 Req.- *Detection limit and ETC calibrations*..... 41

5.6.9 Req.- *Secondary Standards*..... 42

5.7.1 Req.- *Camera focus/tilt*..... 42

5.7.2 Req.- *Ghosts - ADC*..... 43

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 81

A2 LIST of RAW CALIBRATION DATA

	volume per req.run and per year
RawData– 523 <i>CCD gain</i>	10Gb 0.52 Tb
RawData– 531 <i>Dark current</i>	0.75Gb 40Gb
RawData– 533 <i>CCD Linearity</i>	2Gb 24Gb
RawData– 541 <i>Raw Bias frame</i>	5Gb 0.51 Tb
RawData– 542 <i>Dome flat frame</i>	2Gb 0.66 Tb
RawData– 543 <i>Twilightflat frame</i>	10Gb 3.3 Tb
RawData– 547 <i>Quick check</i>	0.5Gb 115Gb
RawData– 562 <i>Monitor</i>	0.5Gb 0.5 Tb
RawData– 563 <i>Zeropoint- Key</i>	2.5Gb 0.8 Tb
RawData– 564 <i>Zeropoint - User</i>	2.5Gb 0.8 Tb
RawData– 565 <i>User – >key</i>	25Gb 25Gb
RawData– 569 <i>Secondary Standards</i>	32 Gb 4 Tb

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 82

A3 LIST of DFS I/O CALIBRATION FILES

volume per file and per year

CalFile– 521 <i>Readout noise</i>	2 kb, 1 Mb
CalFile– 522 <i>bad/hot pixel map</i>	0.25Gb 25Gb
CalFile– 523 <i>conversion factor e^-/ADU</i>	2kb .1Mb
CalFile– 531 <i>dark count rate for each CCD</i>	2kb .1Mb
CalFile– 532 <i>Particle event rate</i>	2kb .1Mb
CalFile– 533 <i>CCD Linearity</i>	2kb .1Mb
CalFile– 534 <i>charge transfer efficiency factors</i>	.2Mb .4Mb
CalFile– 535 <i>cold pixel map</i>	.25Gb 1Gb
CalFile– 536 <i>CCD Hysteresis</i>	2kb 2kb
CalFile– 541 <i>Master Bias frame</i>	1Gb 104Gb
CalFile– 542 <i>Master Domeflat frame</i>	1Gb 0.330 Tb
CalFile– 542L <i>Dome Lamp</i>	2kb 1Mb
CalFile– 543 <i>Master Twilightflat frame</i>	4Gb 1.3 Tb
CalFile– 544 <i>Nightsky flat frame</i>	1Gb 1 Tb
CalFile– 545 <i>ff-fringe</i>	1Gb 0.3 Tb
CalFile– 546 <i>Master flatfield</i>	1Gb 0.3 Tb
CalFile– 546W <i>Weightmap</i>	1Gb 0.3 Tb
CalFile– 547 <i>Quick check</i>	1Gb 0.33 Tb
CalFile– 547r <i>Quick check - day report</i>	3kb 1Mb
CalFile– 548 <i>Illumination correction</i>	1Gb 10Gb
CalFile– 551 <i>Astrometric camera/chip solution</i>	2kb .1Mb
CalFile– 554 <i>PSF anisotropy</i>	.1Mb 1 Mb
CalFile– 556 <i>Astrometric solution - Guide CCD</i>	2 kb 1 Mb
CalFile– 562S <i>Sky brightness</i>	1 kb 1 kb
CalFile– 562 <i>Extinction-night report</i>	2 kb 1 Mb
CalFile– 562u <i>Photom + Sky</i>	10Mb 10Gb
CalFile– 562B <i>Photom + Sky</i>	10Mb 10Gb
CalFile– 562V <i>Photom + Sky</i>	10Mb 10Gb
CalFile– 562i <i>Photom + Sky</i>	10Mb 10Gb
CalFile– 563Z <i>Zeropoint - key bands</i>	4kb 1.2Mb

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 83

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

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 84

A4 LIST of DFS INPUT REFERENCE CATALOGUES

CalFile– in1 <i>US-NAVAL Observatory A2.0</i>	6 Gbyte
CalFile– 569E <i>Primary Standard stars - external Landolt fields</i>	100 Mb
CalFile– 569E <i>Primary Standard stars - external WFI@2.2</i>	100 Mb
CalFile– 564E <i>Standard extinction curve</i>	0.1Mb

NOVA - Kapteyn Institute USM – OaPd	OmegaCAM	ID VST-SPE-OCM-23100-3051
	DRS	Issue VERSION 1.1 Date 29 Oct 2001 Page 85

A5 LIST of SEQUENTIAL STEPS in IMAGE PIPELINE

- 6.3.1 Seq.– *Initialization and image statistics* 58
- 6.3.2 Seq.– *Trim, de-bias, flatfield* 60
- 6.3.3 Seq.– *Construct individual weights* 60
- 6.3.4 Seq.– *Astrometric calibration*..... 62
- 6.3.5 Seq.– *Apply photometric calibration* 64
- 6.3.6 Seq.– *Co-addition*..... 65