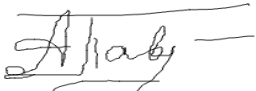


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|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|

# SPHERE

## Data Reduction Pipeline Manual

| Contr | Man-PA | Sci | Syst | INS | DRH | CPI | IRD | IFS | ZIM |
|-------|--------|-----|------|-----|-----|-----|-----|-----|-----|
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| <i>Prepared by:</i><br><b>Name:</b> Ole Möller-Nilsson<br><b>Institute:</b> MPIA<br><b>Date:</b> 28-11-2014 | <i>Signature:</i><br> |
| <i>Approved by:</i><br><b>Name:</b> Alexey Pavlov<br><b>Institute:</b> MPIA<br><b>Date:</b> 28-11-2014      | <i>Signature:</i><br> |
| <i>Released by:</i><br><b>Name:</b> Markus Feldt<br><b>Institute:</b> MPIA<br><b>Date:</b> 28-11-2014       | <i>Signature:</i><br> |

Contributors: Alexey Pavlov, Christian Thalmann, Joe Carson and Markus Feldt, MPIA

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# Chapter 1

## Introduction

### 1.1 Purpose

The SPHERE pipeline is a subsystem of the VLT Data Flow System (DFS). It is used in two operational environments, for the ESO Data Flow Operations (DFO), and for the Paranal Science Operations (PSO), in the quick-look assessment of data, in the generation of master calibration data, in the reduction of scientific exposures, and in the data quality control. Additionally, the SPHERE pipeline recipes are made public to the user community, to allow a more personalised processing of the data from the instrument.

The purpose of this document is to describe a typical SPHERE data reduction sequence with the SPHERE pipeline. This manual is a complete description of the data reduction recipes offered by the SPHERE pipeline, reflecting the status of the SPHERE pipeline as of 29th July 2016 (version 0.19.0).

### 1.2 Scope of this document

This document describes the data reduction library for the Sphere instrument on VLT. It is part of the deliverables.

The main purpose of this document is to present and explain the data reduction software (in form of a library) for SPHERE in general and IFS, IRDIS and ZIMPOL in particular. The structure and content of this document follows the guidelines set out in the ESO document “Data Flow for VLT/VLTI Instruments Deliverables Specifications” (VLT-SPE-ESO-19000-1618).

The document presented here follows the layout presented in section 4.5.1 of the “Data Flow for VLT/VLTI Instruments Deliverables Specifications” closely with the exception of an added introduction (chapter 1 in this document) and an overview (chapter 2).

The present document describes the design of the data reduction software, including detailed descriptions of algorithms and functions and explains how to reduce SPHERE data with it.

The examples on running individual pipeline recipes in this manual use the `esorex` command and manually created list of input files. Several interfaces to automatically organise the data, create the list of input files and execute the pipeline recipes in the proper sequence are available, see <https://www.eso.org/pipelines> for details.

Please note that the use of Gasgano as a GUI for processing data is deprecated. Its use is no longer recommended and the related section in this manual, as well as support for Gasgano as a

data processing GUI application in general will be dropped entirely in a future release.

The instrument and detector calibrations as discussed here assume that the hardware requirements for the various sub-systems and specified in the corresponding documents are met and that there are no unforeseen instrument signatures.

## 1.3 Acknowledgments

## 1.4 Change Record

| Issue | Rev. | C.S                                                    | change                                                                                                                                                                                                                                         | Date       | Comment                                          |
|-------|------|--------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|--------------------------------------------------|
| 0     | 1    |                                                        |                                                                                                                                                                                                                                                |            | Initial Draft                                    |
| 0     | 2    |                                                        |                                                                                                                                                                                                                                                | 5-8-2010   | IFS AIT Release I                                |
| 0     | 3    |                                                        |                                                                                                                                                                                                                                                | 1-9-2010   | IRDIS AIT Release I                              |
| 0     | 4    |                                                        |                                                                                                                                                                                                                                                | 26-11-2010 | November (“Virgo”) Release                       |
| 0     | 5    |                                                        | Updated/changed recipe descriptions for detector related recipes (dark, ron, gain, flat, ifs_persistence). Added output keywords                                                                                                               | 9-3-2011   | Libra release.                                   |
| 0     | 6    |                                                        | Added new ZIMPOL recipes. Updated description of wavelength related IFS recipes (spectra_positions, instrument_flat,...)                                                                                                                       | 15-4-2011  | Scorpio release.                                 |
| 0     | 7    |                                                        |                                                                                                                                                                                                                                                | 5-10-2011  | Release for DRH Science meeting (version 0.11.1) |
| 0     | 8    |                                                        |                                                                                                                                                                                                                                                | 27-7-2012  | PAE internal release                             |
| 1     | 0    | 6<br>3.x<br>9.2<br>9.14<br>A.1<br>3.3<br>3.3<br>8,9,10 | Data description updated<br>Chapter Removed, now sec.2.1<br>Updated description of flatfield<br>Deleted IFS RON recipe<br>QC keywords moved to appendix<br>Adapted example description to match PAE data set<br>updated recipe manual sections | 16-10-2013 | Ready PAE Release                                |
| 1     | 1    |                                                        | Restructured                                                                                                                                                                                                                                   | 02-11-2015 | V 16                                             |
| 1     | 16   | 3.2,3.3,3.4                                            | Updated Workflows and recipe descriptions                                                                                                                                                                                                      | 15-02-2016 |                                                  |
| 1     | 19   | 3.2,3.3,3.4                                            | Updated Workflows and recipe descriptions                                                                                                                                                                                                      | 25-07-2016 |                                                  |

## 1.5 Applicable Documents

| No. | Document name                                                     | Document number,<br>Iss./Rev. |
|-----|-------------------------------------------------------------------|-------------------------------|
| AD1 | VLT instrumentation software specifications                       | VLT-SPE-ESO-17212-0001        |
| AD2 | Field and Pupil Rotation for the VLT Units                        | VLT Report No.63, ESO 1990    |
| AD3 | Data Flow for VLT/VLTI Instruments:<br>Deliverables Specification | VLT-SPE-ESO-19000-1618/2.0    |
| AD4 | Common Pipeline Library Technical Developers<br>Manual            | VLT-MAN-ESO-19500-3349        |
| AD5 | Common Pipeline Library User Manual                               | VLT-MAN-ESO-19500-2720        |
| AD6 | IFS Calibration Plan                                              | VLT-PLA-SPH-14690-0200        |
| AD7 | Data Flow for VLT/VLTI Instruments:<br>Deliverables Specification | VLT-SPE-ESO-19000-1618/2.0    |
| AD8 | IRDIS Data Reduction Library Design                               | VLT-TRE-SPH-14690-351         |
| AD9 | SPHERE Science Analysis Report                                    | VLT-TRE-SPH-14609-235         |

## 1.6 Reference Documents

| No.  | Document name                                                                | Document number,<br>Iss./Rev.                                                                                     |
|------|------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|
| RD1  | Efficient algorithms for robust feature matching.                            | D.M.Mount, N.S.Netanyahu,<br>J.Le Moigne, Pattern<br>Recognition vol.32 (1999)<br>pp.17-38.                       |
| RD2  | Frame combination techniques for<br>ultra-high-contrast imaging              | Carson et al.2008, SPIE, 7014E,<br>115C                                                                           |
| RD3  | IRACproc: a software suite for processing and<br>analyzing Spitzer/IRAC data | Schuster et al.2006, SPIE,<br>6270E, 65S                                                                          |
| RD4  | HST Dither Handbook                                                          | Koekemoer et al.2000,<br>[Baltimore: STScI]                                                                       |
| RD5  | Frame combination using Drizzle                                              | Fruchter, A.S and Hook, R.N<br>1997 in Proc.SPIE, Vol.3164                                                        |
| RD6  | Euro3D Format                                                                | M.Kissler-Pattig et al., Issue<br>1.2, May 2003                                                                   |
| RD7  | IFS Simulation report                                                        | VLT-TRE-SPH-14690-0195                                                                                            |
| RD8  | IFS Calibration Plan                                                         | VLT-PLA-SPH-14690-0200                                                                                            |
| RD9  | Gasgano User's Manual.                                                       | <a href="http://www.eso.org/gasgano/">http://www.eso.org/gasgano/</a><br>VLT-PRO-ESO-19000-1932.13,<br>15, 19, 28 |
| RD10 | SPHERE User Manual                                                           | VLT-MAN-SPH-14690-0430                                                                                            |
| RD11 | SPHERE DRH Test Plan and Report                                              | VLT-PLA-SPH-14690-0659/2/0                                                                                        |

## 1.7 Acronyms

| Acronym | Meaning                                                         | Mathematical representation             |
|---------|-----------------------------------------------------------------|-----------------------------------------|
| ANSI-C  | The standardized programming language C                         |                                         |
| API     | Advanced Programming Interface                                  |                                         |
| CCD     | Charge Coupled Device                                           |                                         |
| CFITSIO | A library for accessing FITS files in C                         |                                         |
| CPL     | Common Pipeline Library                                         |                                         |
| CVS     | Concurrent Version System                                       |                                         |
| DBI     | Double Imaging Mode                                             |                                         |
| DC      | Dark current                                                    | $DC(x, y)$                              |
| DF      | Detector flat field – the pixel response to an input signal.    | $DF(x, y)$                              |
| DIT     | Detector Integration Time                                       |                                         |
| DRH     | Data Reduction Handling                                         |                                         |
| DPI     | Double Polarization Imaging                                     |                                         |
| DPR     | Data Product                                                    |                                         |
| ESO     | European Southern Observatory                                   |                                         |
| FDR     | Final Design Review                                             |                                         |
| FoV     | Field of View                                                   |                                         |
| FPN     | Fixed Pattern Noise                                             | $FPN(x, y)$                             |
| GSL     | Gnu Scientific Library                                          |                                         |
| HDU     | Hierarchical Detector Unit                                      |                                         |
| HST     | Hubble Space Telescope                                          |                                         |
| HWP     | Half-wave plate                                                 |                                         |
| IF      | Instrument flat field – the lenslet response to an input signal | $IF(x, y; \Delta x, \Delta y, \lambda)$ |
| IFS     | The SPHERE integral field spectrograph instrument               |                                         |
| IFU     | Integral Field Unit.                                            |                                         |
| IRDIS   | Sphere imaging instrument                                       |                                         |
| LRS     | Low Resolution Spectroscopy                                     |                                         |
| LDT     | Lenslet Description Table                                       |                                         |
| MRS     | Medium Resolution Spectroscopy                                  |                                         |
| PAE     | Preliminary Acceptance Europe                                   |                                         |
| PDR     | Preliminary Design Review                                       |                                         |
| PDT     | Pixel Description Table                                         |                                         |
| PRO     | Product (FITS keywords)                                         |                                         |
| PSF     | Point Spread Function                                           |                                         |
| QC      | Quality Control                                                 |                                         |
| RON     | Read out noise                                                  | $RON$                                   |
| SVN     | “Subversion”– a revision control management system              |                                         |
| TBC     | To be confirmed                                                 |                                         |
| TBD     | To be decided                                                   |                                         |
| TF      | Telescope flat field – the flat field response of the telescope | $TF(x, y; \Delta x, \Delta y, \lambda)$ |
| VLT     | Very Large Telescope                                            |                                         |
| ZPL     | Zurich Imaging POLarimeter                                      |                                         |

## Chapter 2

# Overview

In collaboration with instrument consortia, the Data Flow Systems Department (DFS) of the Data Management and Operation Division is implementing data reduction pipelines for the most commonly used VLT/VLTI instrument modes. These data reduction pipelines have the following three main purposes:

- Data quality control: pipelines are used to produce the quantitative information necessary to monitor instrument performance.
- Master calibration product creation: pipelines are used to produce master calibration products (e.g. combined dark frames, super-flats, wavelength dispersion solutions).
- Science product creation: using pipeline-generated master calibration products, science products are produced for the supported instrument modes.

The accuracy of the science products is limited by the quality of the available master calibration products and by the algorithmic implementation of the pipelines themselves. In particular, adopted automatic reduction strategies may not be suitable or optimal for all scientific goals.

Instrument pipelines consist of a set of data processing modules that can be called from the command line, from the automatic data management tools available on Paranal or from Gasgano. ESO offers two front-end applications for launching pipeline recipes, Gasgano [14] and EsoRex, both included in the pipeline distribution. These applications can also be downloaded separately from <http://www.eso.org/gasgano> and <http://www.eso.org/cpl/esorex.html>. An illustrated introduction to Gasgano is provided in the "Quick Start" Section 3.1 of this manual. Workflows for individual data reduction cascades and detailed descriptions of each recipe's inputs, outputs, parameters and operations can be found in Sections 3.2, 3.3, and 3.4.

The SPHERE instrument and the different types of SPHERE raw frames and auxiliary data are described in Chapter 4.

A detailed mathematical description of operations carried out inside recipes is given in Chapter 5.

In Chapter 6 the installation of the SPHERE pipeline recipes is described together with a few solutions to frequent problems.

## 2.1 The SPHERE Instrument: IFS, IRDIS and ZIMPOL

In addition to this document, there is the SPHERE user manual [RD10] which gives a brief introduction to the instrument, as well as a general description of the available observing instruments

and modes, and details about setting up actual observations.

## Chapter 3

# Pipeline Guide

This section describes the most immediate usage of the SPHERE pipeline recipes. If you are unfamiliar with ESO pipelines and the plugins called recipes, you can find a basic description of how to operate these things in 3.1. An example workflow for a data set supposedly taken in an IRDIS

observing sequence is described in 3.1.4. More detailed information on the workflow for each instrument and individual recipes can be found in ...

### 3.1 Quick Start

#### 3.1.1 An introduction to Gasgano and EsoRex

Before being able to call pipeline recipes on a set of data, the data must be opportunely classified, and associated with the appropriate calibrations. The Data Classification consists of tasks such as: "What kind of data am I?", e.g., DARK, "to which group do I belong?", e.g., to a particular ObservationBlock or template. Data Association is the process of selecting appropriate calibration data for the reduction of a set of raw science frames. Typically, a set of frames can be associated if they share a number of properties, such as instrument and detector configuration. As all the required information is stored in the FITS headers, data association is based on a set of keywords (called "association keywords") and is specific to each type of calibration. The process of data classification and association is known as data organisation. The DO Category is the label assigned to a data type as a result of data classification. An instrument pipeline consists of a set of data processing modules that can be called from different host applications, either from the commandline with EsoRex, from the automatic data management tools available at Paranal, or from the graphical Gasgano tool. Gasgano is a data management tool that simplifies the data organisation process, offering automatic data classification and making the data association easier (even if automatic association of frames is not yet provided).

Gasgano determines the classification of a file by applying an instrument specific rule, while users must provide this information to the recipes when they are executed manually using EsoRex from the command line. In addition, Gasgano allows the user to execute directly the pipeline recipes on a set of selected files.

#### 3.1.2 Using Gasgano

To get familiar with the SPHERE pipeline recipes and their usage, it is advisable to begin with Gasgano, because it provides a complete graphic interface for data browsing, classification and asso-

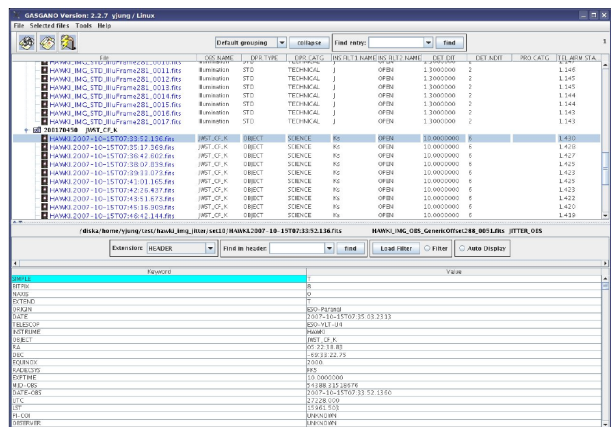


Figure 3.1: The Gasegano main window

ciation, and offersseveral other utilities such as easy access to recipes documentation andpreferred data display tools.Gasegano can be started from the Command Line Interface in the followingway: gasegano & Figure 4.2.1 shows the Gasegano main window.

With the pull-down-menu File->Add/Remove Files directories containing SPHEREdata can be added.The data are hierarchically organised as preferred by the user.After each file name are shown the classification, the template id, theoriginal file name, the template exposure number and the number of exposuresin the template.More information about a single frame can be obtained by clicking on itsname: the corresponding FITS file header will be displayed on the bottompanel, where specific keywords can be opportunely filtered and searched.Images and tables may be easily displayed using the viewers specified inthe appropriate Preferences fields.

Frames can be selected from the main window with a <CTRL>-left-click forprocessing by the appropriate recipe: on Figure 4.2 a set of calibrationFITS-files have been selected and after selecting the appropriate recipe,the depicted Gasegano recipe execution window will open, having all thespecified files listed in its Input Frames panel.Help about the recipe may be obtained from the Help menu.Before launching the recipe, its parameters may be modified on the Parameterspanel (on top).The window contents might be saved for later use by selecting the SaveCurrent Settings entry from the File menu, as shown in figure.At this point the recipe can be launched by pressing the Execute button.Messages from the running recipe will appear on the Log Messages panelat bottom, and in case of successful completion the products will be listedon the Output Frames panel, where they can be easily viewed and locatedback on the Gasegano main window.Please refer to the Gasegano User’s Manual [RD9] for a more complete descriptionof the Gasegano interface.

### 3.1.3 Using EsoRex

EsoRex is a command line utility for running pipeline recipes.It may be embedded by users into data reduction scripts for the automationof processing tasks.On the other side, EsoRex doesn’t offer all the facilities available withGasegano, and the user must classify and associate the data using the information contained in the FITS header keywords (see Section 6).The user should also take care of defining the input set-of-frames andthe appropriate configuration parameters for each recipe run: The set-of-frames: Each pipeline recipe is run on a set of input FITS data files.When using EsoRex the file names must be listed together with their DOcategory in an ASCII file, the set-of-frames (SOF), that is required whenlaunching a recipe.Here is an example of SOF, valid for the sph\_ird\_instrument\_flat recipe:

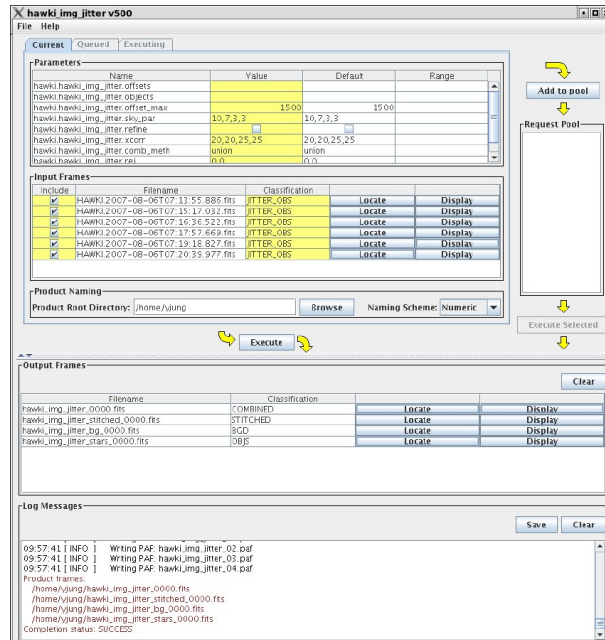


Figure 3.2: The Gasgano recipe execution window

```

/data/calib/master_dark.fits          IRD_MASTER_DARK
/data/2011-03-27/raw_flat_bright_DIT_0.fits  IRD_FLAT_FIELD_RAW
/data/2011-03-27/raw_flat_bright_DIT_1.fits  IRD_FLAT_FIELD_RAW
/data/2011-03-27/raw_flat_bright_DIT_2.fits  IRD_FLAT_FIELD_RAW

```

Note that the SPHERE pipeline recipes do not verify the correctness of the DO category specified by the user in the SOF. The reason of this lack of control is that SPHERE recipes are just one component of the complete pipeline running on Paranal, where the task of data classification and association is carried out by separate applications. Using Gasgano as an interface to the pipeline recipes will however ensure a correct classification of all the data frames, assigning the appropriate DO category to each one of them (see section 4.2.1). A recipe handling an incorrect SOF may stop or display unclear error messages at best. In the worst cases, the recipe would apparently run without any problem, producing results that may look reasonable, but are actually flawed.

**EsoRex syntax:**

The basic syntax to use ESOREX is the following:

`esorex [esorex_options] recipe_name [recipe_options] set_of_frames`

To get more information on how to customise ESOREX (see also [13]) run the command:

`esorex --help`

To generate a configuration file `esorex.rc` in the directory `$HOME/.esorex` run the command:

`esorex --create-config`

A list of all available recipes, each with a one-line description, can be obtained using the command:

`esorex —recipes`

All recipe parameters (aliases) and their default values can be displayed by the command

`esorex —params recipe_name`

To get a brief description of each parameter meaning execute the command:

`esorex —help recipe_name`

To get more details about the given recipe give the command at the shell prompt:

`esorex —man—page recipe_name`

### 3.1.3.1 Recipe configuration:

Each pipeline recipe may be assigned an EsoRex configuration file, containing the default values of the parameters related to that recipe. The configuration files are normally generated in the directory `$HOME/.esorex`, and have the same name as the recipe to which they are related, with the file name extension `.rc`. For instance, the recipe `sph_ifs_master_dark` has its EsoRex generated configuration file named `sph_ifs_master_dark.rc`, and is generated with the command:

`esorex —create—config sph_ifs_master_dark`

The definition of one parameter of a recipe may look like this:

```
# --ifs.master_dark.clean_mean.reject_high
# Reject high.
ifs.master_dark.clean_mean.reject_high=2
```

In this example, the parameter `ifs.master_dark.clean_mean.reject_high` (controlling the number of outliers at the high end to discard when combining frames) is set to the value 2. In the configuration file generated by EsoRex, one or more comment lines are added containing information about the possible values of the parameter, and an alias that could be used as a command line option. The recipes provided by the SPHERE pipeline are designed to be usable in a cascade of data reduction steps, each controlled by its own parameters. For this reason and to prevent parameter name clashes we specify as parameter prefix not only the instrument name but also the name of the step they refer to. Shorter parameter aliases are made available for use on the command line. The command

`esorex —create—config recipe_name`

generates a default configuration file `recipe_name.rc` in the directory `$HOME/.esorex`. A recipe configuration file different from the default one can be specified on the command line:

`esorex —recipe—config=my_alternative_recipe_config`

Recipe parameters are provided in Section 9. More than one configuration file may be maintained for the same recipe but, in order to be used, a configuration file not located under `$HOME/.esorex`, or having a name different from the recipe name, should be explicitly specified when launching a recipe.

### 3.1.3.2 Recipe execution:

A recipe can be run by specifying its name to EsoRex, together with the name of a set-of frames. For instance, the following command line would be used to run the recipe `sph_ifs_master_dark` for processing the files specified in the set-of-frames `sph_ifs_master_dark.sof`:

```
esorex sph_ifs_master_dark sph_ifs_master_dark.sof
```

The recipe parameters can be modified either by editing directly the used configuration file, or by specifying new parameter values on the command line using the command line options defined for this purpose. Such command line options should be inserted after the recipe name and before the SOF name, and they will supersede the system defaults and/or the configuration file settings. For instance, to set the `sph_ifs_master_dark reject_high` parameter to 4 the following should be typed:

```
esorex sph_ifs_master_dark --ifs.master_dark.clean_mean.reject_high=4
sph_ifs_master_dark.sof
```

For more information on EsoRex, see [13].

## 3.1.4 Example IRDIS Reduction

### 3.1.4.1 Data set

The data set used in this example is the one used to generate the test sequence IRDIS-01 in RD11. It can be obtained from <http://www.mpia.de/SPHERE/sphere-web/IRDIS-01.tar.gz>. This contains the raw data files used in the test described in RD11 and outlined below. There is no subdirectory structure in the tar file, so it is best to create a suitable subdirectory from your working directory and unpack the tarfile in there. The following examples will assume that this directory is named "Raw".

### 3.1.4.2 Creation of the master dark

To create the master dark, the recipe `sph_ird_master_dark` must be run. In the `IRDIS_EXAMPLE_DATA` directory create a file called e.g. "master\_dark.sof" which should look like this:

```
Raw/SPHERE_IRDIFS_DARK_IRDIS210_0001.fits      IRD_DARK_RAW
Raw/SPHERE_IRDIFS_DARK_IRDIS210_0002.fits      IRD_DARK_RAW
```

Now run

```
esorex sph_ird_master_dark \
--ird.master_dark.clean_mean.reject_low=0 \
--ird.master_dark.clean_mean.reject_high=0 \
master_dark.sof
```

to execute the recipe. By the way: A call with

```
esorex --man-page sph_ird_master_dark
```

provides you with a help page.

The recipe will run for a less than a minute. It will then output (your mileage may vary):

```
....
[ INFO ] esorex: Created product master_dark.fits (in place)
```

```
[ INFO ] esorex: Created product static_badpixels.fits (in place)
[ INFO ] esorex: 2 products created
[ INFO ] esorex: Recipe operation(s) took
43 seconds to complete.
[ INFO ] esorex: Total size of 3 raw input frames = 729.95 MB
[ INFO ] esorex: => processing rate of 16.96 MB/sec
```

The first of these is the master dark, the second the bad pixels in a separate file. View it with your favourite FITS viewer and compare with the input files to verify that it is indeed the mean of the inputs. Notice that the master\_dark.fits file has 3 additional extensions – look at all of them using e.g. ds9 by calling (1 stands for the first extension):

```
ds9 sph_ird_master_dark.fits [1]
```

Later in this manual you can find a description of the recipe in detail and what is stored in the other extensions.

### 3.1.4.3 Creating the master flat

Similarly to the creation of the master\_dark, now create a file called master\_flat.sof with the content:

```
Raw/SPHERE_IRDIFS_FLAT_IRDIS210_0004.fits    IRD_FLAT_FIELD_RAW
Raw/SPHERE_IRDIFS_FLAT_IRDIS210_0005.fits    IRD_FLAT_FIELD_RAW
Raw/SPHERE_IRDIFS_FLAT_IRDIS210_0006.fits    IRD_FLAT_FIELD_RAW
Raw/SPHERE_IRDIFS_FLAT_IRDIS210_0007.fits    IRD_FLAT_FIELD_RAW
Raw/SPHERE_IRDIFS_FLAT_IRDIS210_0008.fits    IRD_FLAT_FIELD_RAW
```

Run the recipe using

```
esorex sph_ird_instrument_flat master_flat.sof
```

Again note the the resulting file, irdis\_flat.fits has in total 4 data units/extensions.

You should also experiment with using different parameters. For example, rerun the recipe with

```
esorex sph_ird_instrument_flat \
—ird_instrument_flat.threshold=0.9 \
master_flat.sof
```

look at the output irdis\_flat.fits and the first (bad pixel) extension irdis\_flat.fits[1] to see the difference.

You may also add a line to the .sof file like

```
master_dark.fits    IRD_MASTER_DARK
```

to learn about the influence of supplying a pre-determined dark.

### 3.1.4.4 Distortion Map

To correct for the instruments distortion, a specific map is generated from dedicated calibration data. The corresponding recipe is called “sph\_ird\_distortion\_map”, and a good “distort.sof” would look like:

```
Raw/SPHERE_IRDIS072_0004.fits
IRD_DISTORTION_MAP_RAW
master_dark.fits
irdis_flat.fits
```

```
IRD_MASTER_DARK
IRD_FLAT_FIELD
```

In the test, the call for the recipe was

```
esorex sph_ird_distortion_map \
—ird.distortion_map.threshold=2.0 \
distort.sof
```

You can experiment with the threshold parameter to learn why it is important. Like all other recipes that involve CPL functions that do thresholding and peak finding, this one is quite sensitive to the threshold provided and a look at the data may be required before calling the recipe.

Note that since no reference grid is supplied, the recipe assumes that the data provided is the reference and generates a reference point table. This is done on the left quadrant. On the right quadrant, which contains of course the identical grid of points, distortion is subsequently measured. You should thus see very small values in the extensions 8 and 12 of the resulting file `distortion_map.fits`, denoting the distortion in x and y at each pixel.

#### 3.1.4.5 Star center table creation

Now before actually doing the science reduction it is currently necessary to run a prototype version of the `sph_ird_star_center` recipe. This recipe is responsible to create a table of field centers, which are crucial for any science reduction with IRDIS. To create this table, first create `star_center.sof` as

```
Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0034.fits
waffle_lowmask_IRD_STATIC_BADPIXELMAP.fits
master_dark.fits
irdis_flat.fits
```

```
IRD_STAR_CENTER_WAFFLE_RAW
IRD_STATIC_WAFFLEMAP
IRD_MASTER_DARK
IRD_FLAT_FIELD
```

and then run

```
esorex sph_ird_star_center \
—ird.star_center.sigma=1000 \
—ird.star_center.coll_alg=1 \
—ird.star_center.nsources=4 \
star_center.sof
```

which will create a product called `star_center.fits` that contains a fitstable carrying the center coordinates found, a time stamp, and the DMS (Detector Motion Stage) position during the exposure. Not that as again peak finding and thresholding is involved, the corresponding parameters passed to the recipe are quite sensitive, and experimenting is always welcome!

Note also that the `waffle_lowmask_IRD_STATIC_BADPIXELMAP.fits` file is not actually raw data, but simply a mask provided along with the pipeline! You are free to adapt this mask to improve results...

#### 3.1.4.6 Reducing the science data

As the last step the science data is reduced. There are several different recipes available for IRDIS for this step, depending on the mode and the desired algorithm. The standard recipe is the DBI

recipe, sph\_ird\_science\_dbi. To run this, create a new science\_dbi.sof file which has to be identical to the star\_center.sof except for the raw file tag names:

|                                             |                     |
|---------------------------------------------|---------------------|
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0038.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0039.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0040.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0041.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0042.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0043.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0044.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0045.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0046.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0047.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0048.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0049.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0050.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0051.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0052.fits | IRD_SCIENCE_DBI_RAW |
| Raw/SPHERE_IRDIFS_OBJECT_IRDIS210_0053.fits | IRD_SCIENCE_DBI_RAW |
| master_dark.fits                            | IRD_MASTER_DARK     |
| irdis_flat.fits                             | IRD_FLAT_FIELD      |
| distortion_map.fits                         | IRD_DISTORTION_MAP  |
| star_center.fits                            | IRD_STAR_CENTER     |

Note that here not all the science frames in the science\_science directory are included. This is simply to make sure you don't have to wait for several hours for all the data to be reduced!

```
esorex sph_ird_science_dbi science_dbi.sof
```

and the recipe writes as main product a file called science\_dbi.fits. Congratulations, your first IRDIS science reduction has been achieved. Now you can play around with the pipeline to extend your experience and learn about the options you have. The quality of the test data provided is not outstanding, but you can e.g. try to add the option “-ird.science\_dbi.use\_sdi=TRUE” to the esorex command line (*after* the recipe name, as usual!) to get a spectral difference image between the two channels...

## 3.2 IRDIS

IRDIS offers the following basic observing modes:

- Dual-Band Imaging (DBI)
- Classical Imaging (CI)
- Long-Slit Spectroscopy (LSS)
- Dual-Band Polarimetry (DPI)

The calibration cascade consists of a number of basic calibrations which apply to all modes. The recipes for these basic calibrations are presented in . Mode specific calibration recipes are presented in the subsequent subsections. Each recipe description lists the recipe inputs, both raw frames and calibration products. Also given is a description of the recipe's parameters, and of the output product. From these descriptions it should be possible to construct a workflow. A summary is additionally given in .

## 3.2.1 Basic IRDIS Calibrations

### 3.2.1.1 sph\_ird\_gain

#### 3.2.1.1.1 Purpose:

Measure the detector gain

#### 3.2.1.1.2 Input frames:

| Data Type (TAG)          | Source      | Optional | Min | Max |
|--------------------------|-------------|----------|-----|-----|
| IRD_ GAIN_ RAW           | Raw data    | No       | 4   | Any |
| IRD_ STATIC_ BADPIXELMAP | Calibration | Yes      | 0   | 1   |

#### 3.2.1.1.3 Raw frame keywords used:

none

#### 3.2.1.1.4 Parameters:

| Name                              | Type   | Description                                                                                                                                                                                                                                        | Default                | Allowed vals. |
|-----------------------------------|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|---------------|
| ird.gain.outfilename              | string | The output filename for the product. Please also see the esorex documentation for naming of output products.                                                                                                                                       | ird_ gain_ map.fits    | -             |
| ird.gain.save_ addprod            | bool   | Controls if additional products, in this case a badpixel map and the nonlinearity map should be saved. Note that these will only be created in the first place if The vacca method is not used (see below) AND the fitting order is greater than 1 | 0                      | -             |
| ird.gain.nonlin_ filename         | string | The output filename for the non-linearity map. Please also see the esorex documentation                                                                                                                                                            | ird_ nonlin_ map.fits  | -             |
| ird.gain.nonlin_ bpixname         | string | The output filename for the non linear bad pixel map. Please also see the esorex documentation for naming of output products.                                                                                                                      | ird_ nonlin_ bpix.fits | -             |
| ird.gain.coll_ alg                | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean.                                                                                                                                                                               | 2                      | 0,1,2         |
| ird.gain.clean_ mean.reject_ high | int    | The clean mean reject pixels on high end.                                                                                                                                                                                                          | 0                      | 0-20          |
| ird.gain.clean_ mean.reject_ low  | int    | The clean mean reject pixels on low end.                                                                                                                                                                                                           | 0                      | 0-20          |
| ird.gain.order                    | int    | The fitting order to use, can be 1 (for linear only) or 2 ( for lin+quadratic).                                                                                                                                                                    | 2                      | 1-2           |

| Name                    | Type   | Description                                                                                                                                                                                                                                            | Default | Allowed vals. |
|-------------------------|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ird.gain.lin_ tolerance | double | The allowed maximum absolute value of the second order of the polynomial fit. Any pixels that have an absolute value for the second order polynomial coefficient above this value are considered non-linear and marked as bad in the non-linearity map | 100.0   | -             |
| ird.gain.preproc        | bool   | If set to TRUE, the raw frames are first processed to remove any offset trends within data cubes                                                                                                                                                       | 1       | -             |
| ird.gain.vacca          | bool   | Choose the special noise calculation by Vacca et al. (2004) that takes the number of fowler samples into account.                                                                                                                                      | 0       | -             |

### 3.2.1.1.5 Description:

The gain recipe calculates the gain for the detector and derives a mask of nonlinear pixels. The input is assumed to be a series of data cubes, each containing a single extension with  $N > 3$  planes that each contain a single exposure. The mean count for each input cube should be different either by increasing the intensity of the illumination source or by using different exposure times. Note that in the latter case the recipe only produces the correct output if the detector gain is independent of the read out mode. The gain recipe, as well as the ron recipe, have a special optional preprocessing step, which corrects some possible bias due to readout electronics settings by first subtracting the median of each input cube from each image in the cube. The gain recipe offers algorithms to calculate the gain, one straightforward fitting algorithm and a more complex fitting algorithm that takes the correct number of fowler samples into account. The second algorithm is switched on using the vacca user parameter and is preferable for accurate gain determinations but can currently not be used to calculate the detector non-linearity. It is therefore recommended to set the user parameter vacca to 1 when an accurate gain measurement is needed but not non-linearity measurement is needed and 0 in all other cases. In particular for pure monitoring purposes to discover trends in the gain the simpler algorithm is sufficient. For both algorithms the general procedure is similar: The recipes calculate the gain by first collapsing all input cubes to create a single mean image and variance image. The collapse algorithm specified (clean mean by default) and algorithm parameters are used for this process. Once a mean and variance image has been determined the median of the mean image and the corresponding variance is taken as one data point. The collection of input cubes then lead to a collection of data points of median and variance, giving measurements of the variance vs. median relation for the detector. This is then fitted using a polynomial of the specified order (usually 1 or 2). The slope of this curve is the inverse of the gain while the offset gives an estimate of the read out noise. Note that the read out noise estimate obtained here may not be accurate. Please use the dedicated ron recipe to obtain a more accurate estimate of the RON. The estimates of gain and ron are written as keywords in the main recipe product FITS file. If the vacca parameter is set, the recipe corrects the fitting coefficients for the different noise properties expected for different fowler samples. For example, for double correlated reads this corrects the ron by a factor of 2. If the vacca parameter is not set. The recipe determines non linear pixels in a second step. This is done by performing the gain fitting procedure above for each individual pixel. The resulting map of the gain is the data in the first extension of the main product FITS file. Note that the pixel-by-pixel gain values are often very noisy and can not be used to obtain precise gain measurements. Many exposures per input cube are needed to perform accurate pixel fitting. If the fitorder specified is larger than 1, the second order (quadratic) coefficient of the individual pixel fits is saved in an additional FITS file. All pixels that have second order quadratic coefficient larger than the threshold parameter are flagged as non-linear and this resulting map of flags is written out as a third FITS file.

### 3.2.1.1.6 Products:

| Name                | Type        | Description                                                                                                                                                                                                                                                                                                                                                                                |
|---------------------|-------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IRD_ GAIN           | FITS[Im(4)] | The linear coefficient of the Photon Transfer Curve (PTC) as image. The file contains the gain values in the first extensions. The second extension contains the bad pixels (static input bad pixels), the fourth extension contains the reduced chi-squared values. The third extension is not used and contains a zero image. The header contains the main gain measurement and its rms. |
| IRD_ NONLIN         | FITS[Im(4)] | This product is only created if fitorder > 1. It is identical to the main product except that it contains the second (quadratic) coefficients of the pixel fits in the first extension.                                                                                                                                                                                                    |
| IRD_ NONLIN_ BADPIX | FITS[Im(1)] | A simple image flagging all non linear pixels.                                                                                                                                                                                                                                                                                                                                             |

### 3.2.1.2 sph\_ird\_master\_dark

#### 3.2.1.2.1 Purpose:

Creation of the master dark frame

#### 3.2.1.2.2 Input frames:

| Data Type (TAG) | Source   | Optional | Min | Max |
|-----------------|----------|----------|-----|-----|
| IRD_ DARK_ RAW  | Raw data | No       | 1   | Any |

#### 3.2.1.2.3 Raw frame keywords used:

none

#### 3.2.1.2.4 Parameters:

| Name                            | Type   | Description                                                                                                                                       | Default                | Allowed vals. |
|---------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|---------------|
| ird.master_ dark.outfilename    | string | The output filename for the product. Please also see the esorex documentation for naming of output products.                                      | master_ dark.fits      | -             |
| ird.master_ dark.save_ addprod  | bool   | Flag to signal whether additional products - in this case the badpixel map - should be saved.                                                     | 0                      | -             |
| ird.master_ dark.badpixfilename | string | The output filename for the product. Please also see the esorex documentation for naming of output products. Only used if badpixel map requested. | static_ badpixels.fits | -             |
| ird.master_ dark.coll_ alg      | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean.                                                                              | 2                      | 0,1,2         |

| Name                                           | Type   | Description                                                                                                                      | Default | Allowed vals. |
|------------------------------------------------|--------|----------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ird.master_<br>dark.clean_<br>mean.reject_low  | int    | The clean mean reject pixels on low end.                                                                                         | 0       | 0-20          |
| ird.master_<br>dark.clean_<br>mean.reject_high | int    | The clean mean reject pixels on high end.                                                                                        | 0       | 0-20          |
| ird.master_<br>dark.sigma_clip                 | double | Badpixel determination sigma value for clipping.                                                                                 | 5.0     | 0.0-200.0     |
| ird.master_<br>dark.smoothing                  | double | The smoothing length to use for calculation of the large scale dark structures. Smoothing is needed for good hotpixel detection. | 5.0     | 0.0-200.0     |
| ird.master_dark.min_acceptable                 | double | The minimum acceptable value. Any pixels with values below this are marked as bad.                                               | -100.0  | -             |
| ird.master_dark.max_acceptable                 | double | The maximum acceptable value. Any pixels with values above this are marked as bad.                                               | 1000.0  | -             |

#### 3.2.1.2.5 Description:

This recipe deals with the creation of the master dark calibration frame. Only raw frames are used in this recipe. The dark is created by combining the input raw frames using the collapse algorithm specified (usually the clean\_mean algorithm). After all input frames are combined in this way, the badpixels are determined on the result. First a simple thresholding is applied using the parameters min\_accepting and max\_accepting. A smoothed version of the image is then subtracted to remove large scale variations. The smoothing scale can be changed with the corresponding user parameter. Then sigma clipping is used with the sigma user parameter. All pixels that are further than the specified sigma value away from the mean are marked as bad in the combined, unsmoothed image.. This resulting master dark frame is then written out, A separate hotpixel map is also written out.

#### 3.2.1.2.6 Products:

| Name                   | Type        | Description                                                                                                                                                                         |
|------------------------|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IRD_MASTER_DARK        | FITS[Im(4)] | The resulting master dark frame. This frame contains 4 different image extensions: the image, badpixels, the weightmap (how many frames contribute to each pixel), and the rms map. |
| IRD_STATIC_BADPIXELMAP | FITS[Im(1)] | An optionally written single extension image of the static badpixels. Note that the content is identical to the second extension in the master dark frame.                          |

### 3.2.1.3 sph\_ird\_ins\_bg

#### 3.2.1.3.1 Purpose:

Creation of an instrument background

### 3.2.1.3.2 Input frames:

| Data Type (TAG)          | Source      | Optional | Min | Max |
|--------------------------|-------------|----------|-----|-----|
| IRD_ INS_ BG_ RAW        | Raw data    | No       | 1   | Any |
| IRD_ INSTRUMENT_ MODEL   | Calibration | Yes      | 0   | 1   |
| IRD_ STATIC_ BADPIXELMAP | Calibration | Yes      | 0   | 1   |

### 3.2.1.3.3 Raw frame keywords used:

none

### 3.2.1.3.4 Parameters:

| Name                                 | Type   | Description                                                                                                     | Default           | Allowed vals. |
|--------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------|-------------------|---------------|
| ird.ins_ bg.outfilename              | string | The output filename for the product.<br>Please also see the esorex documentation for naming of output products. | ins_ bg.fits      | -             |
| ird.ins_ bg.save_ addprod            | bool   | Flag to signal whether additional products - in this case the smoothed background - should be saved.            | 0                 | -             |
| ird.ins_ bg.lsf_ outfilename         | string | Flag to signal whether additional products - in this case the smoothed background - should be saved.            | ins_ bg_ fit.fits | -             |
| ird.ins_ bg.coll_ alg                | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean.                                            | 2                 | 0,1,2         |
| ird.ins_ bg.clean_ mean.reject_ low  | int    | The clean mean reject pixels on low end.                                                                        | 0                 | 0-20          |
| ird.ins_ bg.clean_ mean.reject_ high | int    | The clean mean reject pixels on high end.                                                                       | 0                 | 0-20          |
| ird.ins_ bg.fitorder                 | int    | The fitting order to use for the 2D polynomial fit of the background.<br>smoothing range double                 | 2                 | 1-7           |

### 3.2.1.3.5 Description:

This recipe deals with the creation of the instrument background calibration frame. Only raw frames are used in this recipe. The background is created by combining the input raw frames using the collapse algorithm specified (usually the clean\_mean algorithm). Contrary to the master\_dark recipe, no badpixel maps are created by this recipe, since thresholding is much more difficult on the background frames. The recommended way to generate a reliable badpixel map is to use the master\_dark recipe on suitable dark frames! MASTER\_DARK, INS\_BG, and SKY\_BG frames are all for subtraction from raw input frames, thus they should never be corrected for flat fields or other dark/background frames!

### 3.2.1.3.6 Products:

| Name | Type | Description |
|------|------|-------------|
|------|------|-------------|

| Name              | Type        | Description                                                                                                                                                                                                                                       |
|-------------------|-------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IRD_ INS_ BG      | FITS[Im(4)] | The resulting master dark frame. This frame contains 4 different image extensions: the image, badpixels, the weightmap (how many frames contribute to each pixel), and the rms map.                                                               |
| IRD_ INS_ BG_ FIT | FITS[Im(4)] | The smoothed frame (2D polynomial fit) of the background. The FITS file contains 4 extensions: the image, the badpixels, the rms error and a weightmap. Left and right frame fits are obtained separately, but inserted into a full frame result! |

### 3.2.1.4 sph\_ird\_sky\_bg

#### 3.2.1.4.1 Purpose:

Creation of a sky background

#### 3.2.1.4.2 Input frames:

| Data Type (TAG)          | Source      | Optional | Min | Max |
|--------------------------|-------------|----------|-----|-----|
| IRD_ SKY_ BG_ RAW        | Raw data    | No       | 1   | Any |
| IRD_ INSTRUMENT_ MODEL   | Calibration | Yes      | 0   | 1   |
| IRD_ STATIC_ BADPIXELMAP | Calibration | Yes      | 0   | 1   |

#### 3.2.1.4.3 Raw frame keywords used:

none

#### 3.2.1.4.4 Parameters:

| Name                              | Type   | Description                                                                                                  | Default         | Allowed vals. |
|-----------------------------------|--------|--------------------------------------------------------------------------------------------------------------|-----------------|---------------|
| ird.sky_bg.outfilename            | string | The output filename for the product. Please also see the esorex documentation for naming of output products. | sky_bg.fits     | -             |
| ird.sky_bg.save_addprod           | bool   | Flag to signal whether additional products - in this case the smoothed background - should be saved.         | 0               | -             |
| ird.sky_bg.lsf_outfilename        | string | Flag to signal whether additional products - in this case the smoothed background - should be saved.         | sky_bg_fit.fits | -             |
| ird.sky_bg.coll_alg               | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean.                                         | 2               | 0,1,2         |
| ird.sky_bg.clean_mean.reject_low  | int    | The clean mean reject pixels on low end.                                                                     | 0               | 0-20          |
| ird.sky_bg.clean_mean.reject_high | int    | The clean mean reject pixels on high end.                                                                    | 0               | 0-20          |

| Name                | Type | Description                                                                                  | Default | Allowed vals. |
|---------------------|------|----------------------------------------------------------------------------------------------|---------|---------------|
| ird.sky_bg.fitorder | int  | The fitting order to use for the 2D polynomial fit of the background. smoothing range double | 2       | 1-7           |

#### 3.2.1.4.5 Description:

This recipe deals with the creation of the sky background calibration frame. Only raw frames are used in this recipe. The background is created by combining the input raw frames using the collapse algorithm specified (usually the `clean_mean` algorithm). Contrary to the `master_dark` recipe, no badpixel maps are created by this recipe, since thresholding is much more difficult on the background frames. The recommended way to generate a reliable badpixel map is to use the `master_dark` recipe on suitable dark frames! `MASTER_DARK`, `INS_BG`, and `SKY_BG` frames are all for subtraction from raw input frames, thus they are never corrected for flat fields or other dark/background frames!

#### 3.2.1.4.6 Products:

| Name           | Type        | Description                                                                                                                                                                                                                                       |
|----------------|-------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IRD_SKY_BG     | FITS[Im(4)] | The resulting master dark frame. This frame contains 4 different image extensions: the image, badpixels, the weightmap (how many frames contribute to each pixel), and the rms map.                                                               |
| IRD_SKY_BG_FIT | FITS[Im(4)] | The smoothed frame (2D polynomial fit) of the background. The FITS file contains 4 extensions: the image, the badpixels, the rms error and a weightmap. Left and right frame fits are obtained separately, but inserted into a full frame result! |

### 3.2.1.5 sph\_ird\_instrument\_flat

#### 3.2.1.5.1 Purpose:

Determine the instrument flat field

#### 3.2.1.5.2 Input frames:

| Data Type (TAG)        | Source      | Optional | Min | Max |
|------------------------|-------------|----------|-----|-----|
| IRD_FLAT_FIELD_RAW     | Raw data    | No       | 2   | 500 |
| IRD_MASTER_DARK        | Calibration | Yes      | 0   | 1   |
| IRD_INS_BG             | Calibration | Yes      | 0   | 1   |
| IRD_INS_BG_FIT         | Calibration | Yes      | 0   | 1   |
| IRD_DARK_RAW           | Raw data    | Yes      | 0   | 500 |
| IRD_STATIC_BADPIXELMAP | Calibration | Yes      | 0   | 1   |
| IRD_INSTRUMENT_MODEL   | Calibration | Yes      | 0   | 1   |

#### 3.2.1.5.3 Raw frame keywords used:

none

### 3.2.1.5.4 Parameters:

| Name                                                | Type   | Description                                                                                                                                                                                                           | Default                        | Allowed vals. |
|-----------------------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|---------------|
| ird.instrument_<br>flat.outfilename                 | string | The output filename for the product.<br>Please also see the esorex documentation for naming of output products.                                                                                                       | irdis_ flat.fits               | -             |
| ird.instrument_<br>flat.robust_ fit                 | bool   | Controls if fitting method is to be a robust linear fit. This will reduce the effect of cosmic rays and other temporary bad pixels. See e.g. Numerical Recipes for a description of the algorithm                     | 0                              | -             |
| ird.instrument_<br>flat.coll_ alg                   | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean. This affects only the first processing step, where the illuminated region is determined. It does not affect the actual flat value determination. | 2                              | 0,1,2         |
| ird.instrument_<br>flat.clean_<br>mean.reject_ high | int    | The clean mean reject pixels on high end. This affects only the first processing step, where the illuminated region is determined. It does not affect the actual flat value determination.                            | 0                              | 0-20          |
| ird.instrument_<br>flat.clean_<br>mean.reject_ low  | int    | The clean mean reject pixels on low end. This affects only the first processing step, where the illuminated region is determined. It does not affect the actual flat value determination.                             | 0                              | 0-20          |
| ird.instrument_<br>flat.save_ addprod               | bool   | Controls if additional products, in this case a badpixel map should be created.                                                                                                                                       | 0                              | -             |
| ird.instrument_<br>flat.badpixfilename              | string | Controls the filename of the badpixel map, if requested for output. Ignored if no make_ badpix is FALSE.                                                                                                              | instr_ flat_<br>badpixels.fits | -             |
| ird.instrument_<br>flat.badpix_<br>lowtolerance     | double | The minimum linear threshold value thats acceptable. All pixels in the final flat that have values below this value will be marked as bad.                                                                            | 0.1                            | -             |
| ird.instrument_<br>flat.badpix_<br>uptolerance      | double | The maximum linear threshold value thats acceptable. All pixels in the final flat that have values above this value will be marked as bad.                                                                            | 10.0                           | -             |
| ird.instrument_<br>flat.badpix_<br>chisqtolerance   | double | The maximum error value thats acceptable. All pixels in the final flat that have errors above this value will be marked as bad.                                                                                       | 50.0                           | -             |

| Name                              | Type   | Description                                                                                                                                                                                                                                                                                                                                    | Default | Allowed vals. |
|-----------------------------------|--------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ird.instrument_<br>flat.threshold | double | The thresholding to use to detect illuminated regions. Before the flat is determined all pixels that have counts below a value of the threshold times the mean are masked out. Note that this should only give a very rough masking. It is much preferable to select the regions for flat determination using the static badpixel input frame. | 0.1     | -             |

### 3.2.1.5.5 Description:

The instrument flat field recipe for IRDIS is very similar as the detector flat field recipe for IFS, sph\_ifs\_detector\_flat\_field. The flat recipe as described here uses input exposures taken with the narrow band or broad band calibration lamps in any of the IRDIS modes. This flat is used in all subsequent recipes that need to remove the pixel to pixel variation in the signal response of the detector and instrument. It is therefore important that input frames are consistently for one particular instrument configuration and that the resulting flat is applied only to data taken with matching instrument configurations. As input the recipe requires a series of flat exposures with different median count levels. This may either be achieved by varying the lamp intensity (preferred) or more commonly by varying the exposure time. Dark handling in this recipe is special: For best results, the recipe needs a series of raw dark frames with DITs matching those of the raw flat field frames. If raw darks are provided, the recipe will for each raw flat field frame select the raw dark with the closest matching DIT and subtract it. the recipe will not insist on perfectly matching DITs, this is the user's responsibility! If raw darks are unavailable (e.g. in a automated pipeline context), the recipe can also apply standard irdis background frames. Note that in this case a single dark frame will be subtracted from all input frames. Best results can thus be achieved only if all input raw flat fields have the same DIT (matching that of the background, of course) and lamp intensity is varied to achieve variable flux. The order of selecting what actually happens is the following:

1. If raw darks are available, all others are ignored.
2. Else if an INS\_BG\_FIT is available, this one is chosen.
3. Else if an INS\_BG is available, this one is chosen.
4. Else if a MASTER\_DARK is available, this one is chosen.

The recipe will also run without any dark at all! It is thus the user's responsibility to supply adequate background frames to achieve the best possible results! The recipe creates the flats as follows: All raw frames are read in and dark subtracted. The dark subtraction is performed differently than for other recipes, and rather than master darks, the recipe actually uses raw dark or background frames. Since the background varies significantly depending on the chosen detector integration time, a dark with a matching exposure time needs to be subtracted for each flat. If a specific irdis instrument model is provided via an input frame the irdis instrument model is read from that frame, otherwise a default model is used. This model is used to identify the left and right detector windows. In the next step, a mask of the illuminated region is created by combining all input exposures and using a thresholding above the given input threshold value to identify illuminated regions and masking out non-illuminated regions. Any hot pixels known from the master dark or the provided hotpixel mask are also masked out. The flat fielding procedure described below (identical to that for the IFS) is then applied to the left and right windows **seperately**.

1. The mean value is determined for the respective window for all exposures.
2. For every pixel  $p = (x, y)$ , a set of  $m_i, v_i(x, y)$  data pairs are stored with  $m_i$  being the exposure mean value and  $v_i(x, y)$  being the pixel value for exposure  $i$ .
3. The flat field value of pixel  $p(x, y)$  is defined as the slope  $c(x, y)$  of a linear fit F to the data  $m_i, v_i(x, y)$ .
4. This slope  $c(x, y)$  effectively represents the pixel's response to illumination relative to the detector mean response. It *is* the flat field value and comes naturally out of the procedure being close to 1.
5. The fit itself is performed either using a maximum likelihood method or a robust fitting method which minimizes the sum of the absolute value of the deviations rather than the sum of the squares of the deviations (see e.g. Numerical Recipes for the algorithm). The robust fitting method will yield better results when significant outliers (e.g. due to cosmic rays) can be expected.
6. The flat field values are saved as an image as the main product of the recipe.

Additionally, the recipe may also produce a separate output of all pixels that are identified as non-linear. The criteria for non-linearity are set by the user parameters and can be either pixels that have a flat field value outside specified bounds and/or pixels for which the linear fit produces a reduced chi-squared above a given threshold value. Note that non-linearity pixel determination is performed on the entire detector region and not the left and right window separately. For reliable non-linearity flagging using the reduced chi-squared it is necessary to use many high quality input exposures. Since the badpixel treatment is somewhat complicated, some important points: the badpixels that are stored in the master flat field itself as produced by this recipe (the second extension of the main recipe product) contain all the badpixels at this point in the cascade. Pixels that were marked as bad from the input static badpixel map are also marked as bad here. The optional static badpixel output that is produced contains strictly only those pixel that the flat field recipe itself deemed to be bad. This does not necessarily include all the badpixels from the static badpixel input file.

### 3.2.1.5.6 Products:

| Name                     | Type        | Description                                                                                                                                                                                                                                                                                                                   |
|--------------------------|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IRD_ FLAT_ FIELD         | FITS[Im(4)] | The flat field. This is saved as a FITS file with 4 extensions, the flat values, the badpixels (hotpixels and non-linear pixels), a weight map (number of frames that contributed to each pixel), and the rms                                                                                                                 |
| IRD_ STATIC_ BADPIXELMAP | FITS[Im(1)] | Optional output of all the non-linear pixels determined. All pixels as determined in this recipe using the <code>ird.instrument_flat.badpix_tolerance</code> parameters. This map does NOT include all the dark frame badpixels – it really only includes those badpixels that are bad simply due to the flat field criteria. |

### 3.2.1.6 sph\_ird\_distortion\_map

#### 3.2.1.6.1 Purpose:

Creation of the total distortion map

#### 3.2.1.6.2 Input frames:

| Data Type (TAG)           | Source      | Optional | Min | Max |
|---------------------------|-------------|----------|-----|-----|
| IRD_ DISTORTION_ MAP_ RAW | Raw data    | No       | 1   | 500 |
| IRD_ MASTER_ DARK         | Calibration | Yes      | 0   | 1   |
| IRD_ INS_ BG              | Calibration | Yes      | 0   | 1   |
| IRD_ INS_ BG_ FIT         | Calibration | Yes      | 0   | 1   |
| IRD_ SKY_ BG              | Calibration | Yes      | 0   | 1   |
| IRD_ SKY_ BG_ FIT         | Calibration | Yes      | 0   | 1   |
| IRD_ FLAT_ FIELD          | Calibration | Yes      | 0   | 1   |
| IRD_ POINT_ PATTERN       | Calibration | Yes      | 0   | 1   |

#### 3.2.1.6.3 Raw frame keywords used:

none

#### 3.2.1.6.4 Parameters:

| Name                                               | Type   | Description                                                                                                                                                                                                                                                                                  | Default                          | Allowed vals. |
|----------------------------------------------------|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|---------------|
| ird.distortion_<br>map.convert                     | bool   | If this flag is set to TRUE (FALSE is default), the recipe will not create a distortion map. Instead it will convert the point pattern table which must be provided in the sof to either FITS or ASCII format. The filename specified with the outfilename parameter is used for the output. | 0                                | -             |
| ird.distortion_<br>map.outfilename                 | string | The output filename for the product. Please also see the esorex documentation for naming of output products.                                                                                                                                                                                 | distortion_ map.fits             | -             |
| ird.distortion_<br>map.point_ table_<br>filename   | string | The output filename for the product. Please also see the esorex documentation for naming of output products.                                                                                                                                                                                 | distortion_ point_<br>table.fits | -             |
| ird.distortion_<br>map.coll_ alg                   | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean.                                                                                                                                                                                                                         | 2                                | 0,1,2         |
| ird.distortion_<br>map.clean_<br>mean.reject_ high | int    | The clean mean reject pixels on high end.                                                                                                                                                                                                                                                    | 0                                | 0-20          |
| ird.distortion_<br>map.clean_<br>mean.reject_ low  | int    | The clean mean reject pixels on low end.                                                                                                                                                                                                                                                     | 0                                | 0-20          |
| ird.distortion_<br>map.threshold                   | double | The sigma above which point sources are detected.                                                                                                                                                                                                                                            | 3.0                              | 0.0-200.0     |
| ird.distortion_<br>map.fitting_ order              | int    | The degree of the 2D-polynomial fitted to the distortion. The degree is used for both the X- and the Y-direction.                                                                                                                                                                            | 3                                | 0-8           |



| Name                                  | Type   | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Default | Allowed vals. |
|---------------------------------------|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ird.distortion_<br>map.max_distortion | double | The maximal distortion to correct for [pixel]. Any observed point that is found to be further than this threshold from its matching calibration point is excluded from the fitting procedure. To avoid an incorrect matching between an observed point and its calibration point this threshold should not be too large. For a grid of equidistant calibration points this upper limit is half the distance between two neighboring calibration points. For a calibration mask with 73 by 73 points on a 1k by 1k detector this limit is just over 7 pixels. | 7.0     | 0.0-2000.0    |
| ird.distortion_<br>map.full-qc        | bool   | Full quality output wanted. Setting this to TRUE will create various QC images and also use the calculated distortion map to de-distort the input. When this flag is set, processing time of this recipe will increase measureably.                                                                                                                                                                                                                                                                                                                          | 0       | -             |
| ird.distortion_<br>map.user_cent      | bool   | the recipe uses as optical centre the coordinate of the point that is closest to the detector centre of the point pattern, while for the right channel the same point is used.                                                                                                                                                                                                                                                                                                                                                                               | 0       | -             |
| ird.distortion_<br>map.cent_left_x    | double | The optical centre of the left FOV. This is only used if the user_cent parameter is set to TRUE.                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 512.5   | -             |
| ird.distortion_<br>map.cent_left_y    | double | The optical centre of the left FOV. This is only used if the user_cent parameter is set to TRUE.                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 512.5   | -             |
| ird.distortion_<br>map.cent_right_x   | double | The optical centre of the right FOV. This is only used if the user_cent parameter is set to TRUE.                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 512.5   | -             |
| ird.distortion_<br>map.cent_right_y   | double | The optical centre of the right FOV. This is only used if the user_cent parameter is set to TRUE.                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 512.5   | -             |
| ird.distortion_<br>map.align_right    | bool   | When set to true, the distortion correction of the right channel has a fixed shift added to it to align it with the left channel. The added shift is the difference between the optical axis of the left and right channel.                                                                                                                                                                                                                                                                                                                                  | 0       | -             |

### 3.2.1.6.5 Description:

This recipe creates a map of the distortion for the instrument. The raw frames are first reduced like standard science frames in field stabilised mode without dithering. The frame combination is simply done using a clean mean, mean or median combination. If given as input, a dark is subtracted and a flat field applied. Dark handling follows the usual strategy, see man page of sph\_ird\_science\_dbi. For this recipe, providing a dark is optional - it will happily look for points also without subtracting anything in advance! The result frame is then analysed to detect point

sources given the user detection threshold specified. Depending on whether a point pattern is given as one of the input frames or not, the recipe now either:

1. creates a new point pattern (if none was given) from the raw frames or
2. measures the distortion map comparing the observed point pattern with the input point pattern provided.

In case that a new distortion map is created, this is done by

1. finding all points in the real image
2. making a guess of the optical axis. This is assumed to be the coordinates of the point closest to the geometrical centre of the point pattern. The geometrical centre of the point pattern is calculated averaging the positions of all the points belonging to the point pattern. The centre values are measured relative to the extension of the product. In order to obtain the pixel coordinates in the raw frame 1024 has to be added to the right channel x coordinate.
3. shifting the input point pattern so that its most central point has the same coordinates as the optical axis. This means that the central points on real and expected point pattern fall exactly on top of each other.
4. determining the distance between each observed (detected) point and the closest point in the input table.
5. all points that have been found to be further than the max distortion value given as parameter to the recipe are removed.
6. The resulting distortion measurements are then used to calculate two 2D-polynomial fits to create a distortion map in both X and Y for all pixels. Each polynomial has its center of origin on the detector center.

The main product of the recipe is a multi-extension file that gives the distortion map for each IRDIS field of view separately. Other recipes use the polynomial fit as stored in the header of extension 0 and 8 to apply the distortion map. The recipe also produces a number of quality control files when requested to do so. The first is an image of the input point pattern, one total one and one each for the left and right FoVs. In addition the recipe uses the distortion map that has been calculated in the main part of the recipe to correct the input processed raw image. This corrected input is written out as a full detector image as well as left and right FoV subimages. To verify the distortion map is correct the recipe also produces residual distortion QC outputs when full QC output is requested. The absolute residual distortion images are named qc\_residuals\_left.fits and qc\_residuals\_right.fits. While these may show outliers, a high quality distortion measurement should yield residual images with typical values  $< 0.1$ . A stronger test of the quality of the distortion map quality can be made by feeding the full detector control image back into a second run of the distortion map recipe. The resulting distortion map then gives the distortion residuals – and these should all be close to 0. The polynomial fit is available as QC parameters in the distortion map. The polynomial fitting is performed on the point patterns shifted by the centre of the optical axis. The fitting generates two polynomials:  $p_x(x, y)$  and  $p_y(x, y)$  where the first provides the shift in the  $x$  direction for a point of coordinates  $(x, y)$ .  $p_y(x, y)$  refers to the shift in the  $y$  coordinates. The coefficients of the polynomials are written as QC parameters in the form “ESO DRS DIST L X COEFF i\_j” where “L” indicates that the QC parameter belongs to the left FOV (for right FOV “R” is used). The letter “X” indicates that the coefficient belongs to  $p_x(x, y)$  (“Y” is used for  $p_y(x, y)$ ).  $i$  and  $j$  are the powers of  $x$  and  $y$ , i.e.  $x^i y^j$ . The pin point static calibration is shifted to the closest pin-point image. This shift is stored as the estimated optical axis in the keywords “ESO QC DISTMAP OPT AXIS X” and “ESO QC DISTMAP OPT AXIS Y”. Then the polynomial fit is applied as described above and saved as DISTORTION MAP, which is used in later steps of the cascade to correct the optical distortion.

### 3.2.1.6.6 Products:

| Name                 | Type         | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|----------------------|--------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IRD_ DISTORTION_ MAP | FITS[Im(16)] | The resulting distortion map. The distortion map is saved in a FITS file with a total of 16 extensions. The first 4 extensions contain values, badpixels, rms and weightmap for the distortion in the x direction and the next 4 extensions the same information for the distortion in the y direction. The first 8 extension contain the information for the left FOV the next 8 extension the information for the right FOV. Please also note that the image data is currently not used in subsequent recipes – only polynomial fit parameters in the FITS header is used. |
| IRD_ POINT_ PATTERN  | FITS[Table]  | This frame is created only if no input point pattern was provided. The frame contains a new table giving the positions of all points found in the raw frames.                                                                                                                                                                                                                                                                                                                                                                                                                |

### 3.2.1.7 sph\_ird\_star\_center

#### 3.2.1.7.1 Purpose:

Determine the field centre

#### 3.2.1.7.2 Input frames:

| Data Type (TAG)                | Source      | Optional | Min | Max |
|--------------------------------|-------------|----------|-----|-----|
| IRD_ STAR_ CENTER_ WAFFLE_ RAW | Raw data    | No       | 1   | Any |
| IRD_ MASTER_ DARK              | Calibration | Yes      | 0   | 1   |
| IRD_ INS_ BG                   | Calibration | Yes      | 0   | 1   |
| IRD_ INS_ BG_ FIT              | Calibration | Yes      | 0   | 1   |
| IRD_ SKY_ BG                   | Calibration | Yes      | 0   | 1   |
| IRD_ SKY_ BG_ FIT              | Calibration | Yes      | 0   | 1   |
| IRD_ FLAT_ FIELD               | Calibration | Yes      | 0   | 1   |
| IRD_ STATIC_ WAFFLEMAP         | Calibration | Yes      | 0   | 1   |

#### 3.2.1.7.3 Raw frame keywords used:

none

#### 3.2.1.7.4 Parameters:

| Name                        | Type   | Description                                                                                                     | Default          | Allowed vals. |
|-----------------------------|--------|-----------------------------------------------------------------------------------------------------------------|------------------|---------------|
| ird.star_center.outfilename | string | The output filename for the product.<br>Please also see the esorex documentation for naming of output products. | star_center.fits | -             |

| Name                                   | Type   | Description                                                                                                               | Default | Allowed vals. |
|----------------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ird.star_center.coll_alg               | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean.                                                      | 2       | 0,1,2         |
| ird.star_center.clean_mean.reject_high | int    | The clean mean reject pixels on high end.                                                                                 | 1       | 0-20          |
| ird.star_center.clean_mean.reject_low  | int    | The clean mean reject pixels on low end.                                                                                  | 1       | 0-20          |
| ird.star_center.sigma                  | double | The sigma threshold to use for source detection                                                                           | 10.0    | -             |
| ird.star_center.use_waffle             | bool   | Flag to whether to expect a waffle image (4 images in cross formation) or not (single central fit).                       | 1       | -             |
| ird.star_center.qc                     | bool   | If set QC output for this recipe is produced.                                                                             | 0       | -             |
| ird.star_center.save_interprod         | bool   | Flag to signal if intermediate products should be kept                                                                    | 0       | -             |
| ird.star_center.unsharp_window         | int    | Before finding centres an unsharp algorithm is used on the image. This specifies the window width for the mask in pixels. | 4       | -             |

### 3.2.1.7.5 Description:

This recipe creates a table with centre star positions. The input raw frames are each reduced by subtracting the dark and applying the flat provided. Dark handling follows the usual strategy, see man page of sph\_ird\_science\_dbi. For this recipe, providing a dark is optional - it will happily look for points also without subtracting anything in advance! After sorting the frames, the recipe only reduces the image data of the waffle images. An optional mask frame may be given, of the same dimensions as the raw input frames, which allows masking out of regions before the point sources are detected. This can mainly be used on images where despite use of a coronagraph a significant central signal is present. The left and right parts of the illuminated detector regions are extracted and left and right part are seperately analysed using a aperture detection algorithm. The aperture detection algorithm detects all connected regions of at least 4 pixels size (area) that are the given sigma above the background. The so detected waffle stars are then used to contruct a geometric centre of all stars found. This is then the frame centre. The recipe also works for the case that there is only one star (e.g. the coronagraph is out and no waffle stars are formed). After frame centers have been determined for all waffle images an internal table is created with an entry for each waffle image, giving the time of the start of the exposure and the centre information. The recipe reads the position of the IRDIS DMS from the header of the raw frames, divides by 18.0 to convert from micron to pixels, and stores them in the output table.

### 3.2.1.7.6 Known Issues:

While this recipe is functional, its requirements are fully settled. The recipeimplements the current baseline of how star centering is foreseen in IRDIS.

### 3.2.1.7.7 Products:

| Name | Type | Description |
|------|------|-------------|
|------|------|-------------|

| Name              | Type        | Description                                                                                                                                           |
|-------------------|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| IRD_ STAR_ CENTER | FITS[Table] | The table of stellar center positions as a FITS table, with one row for each input raw frame. The order is the same as the order of input raw frames. |

## 3.2.2 IRDIS Dual-Band Imaging (DBI) Specific Calibrations and Science

### 3.2.2.1 sph\_ird\_flux\_calib

#### 3.2.2.1.1 Purpose:

Calibrate the effect of coronagraph

#### 3.2.2.1.2 Input frames:

| Data Type (TAG)                 | Source      | Optional | Min | Max |
|---------------------------------|-------------|----------|-----|-----|
| IRD_ FLUX_ CALIB_ CORO_ RAW     | Raw data    | No       | 1   | 100 |
| IRD_ FLUX_ CALIB_ NO_ CORO_ RAW | Raw data    | No       | 1   | 100 |
| IRD_ MASTER_ DARK               | Calibration | No       | 1   | 1   |
| IRD_ FLAT_ FIELD                | Calibration | No       | 1   | 1   |

#### 3.2.2.1.3 Raw frame keywords used:

| Keyword            | Type   | Optional | Description                                                 |
|--------------------|--------|----------|-------------------------------------------------------------|
| ESO DRS IFS CORONO | string | No       | The keyword that specified if the coronagraph is in or out. |

#### 3.2.2.1.4 Parameters:

| Name                                     | Type   | Description                                                                                                  | Default          | Allowed vals. |
|------------------------------------------|--------|--------------------------------------------------------------------------------------------------------------|------------------|---------------|
| ird.flux_ calib.outfilename              | string | The output filename for the product. Please also see the esorex documentation for naming of output products. | flux_ calib.fits | -             |
| ird.flux_ calib.coll_ alg                | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean.                                         | 2                | 0,1,2         |
| ird.flux_ calib.clean_ mean.reject_ high | int    | The clean mean reject pixels on high end.                                                                    | 1                | 0-20          |
| ird.flux_ calib.clean_ mean.reject_ low  | int    | The clean mean reject pixels on low end.                                                                     | 1                | 0-20          |

#### 3.2.2.1.5 Description:

This recipe calibrates the effect of the coronagraph on the detected number of counts. For this purpose the raw frames with and without coronagraph are reduced separately in the standard way (dark subtraction, flat fielding). The recipe then measures the total flux in the coronagraph and the non-coronagraph frames and saves the ratio as a keyword together with the reduced images.

#### 3.2.2.1.6 Products:

| Name             | Type        | Description                                                |
|------------------|-------------|------------------------------------------------------------|
| IRD_ FLUX_ CALIB | FITS[Im(4)] | The reduced frame with the calibration keywords in header. |

### 3.2.2.2 sph\_ird\_science\_dbi

#### 3.2.2.2.1 Purpose:

Science calibration, DBI mode.

#### 3.2.2.2.2 Input frames:

| Data Type (TAG)          | Source      | Optional | Min | Max |
|--------------------------|-------------|----------|-----|-----|
| IRD_ SCIENCE_ DBI_ RAW   | Raw data    | No       | 1   | 500 |
| IRD_ MASTER_ DARK        | Calibration | Yes      | 0   | 1   |
| IRD_ INS_ BG             | Calibration | Yes      | 0   | 1   |
| IRD_ INS_ BG_ FIT        | Calibration | Yes      | 0   | 1   |
| IRD_ SKY_ BG             | Calibration | Yes      | 0   | 1   |
| IRD_ SKY_ BG_ FIT        | Calibration | Yes      | 0   | 1   |
| IRD_ FLAT_ FIELD         | Calibration | No       | 1   | 1   |
| IRD_ DISTORTION_ MAP     | Calibration | Yes      | 0   | 1   |
| IRD_ FILTER_ TABLE       | Calibration | Yes      | 0   | 1   |
| IRD_ STAR_ CENTER        | Calibration | Yes      | 0   | 1   |
| IRD_ FCTABLE             | Calibration | Yes      | 0   | Any |
| IRD_ STATIC_ BADPIXELMAP | Calibration | Yes      | 0   | 1   |

#### 3.2.2.2.3 Raw frame keywords used:

| Keyword             | Type   | Optional | Description |
|---------------------|--------|----------|-------------|
| ESO INS1 OPTI2 NAME | string | No       |             |

#### 3.2.2.2.4 Parameters:

| Name                                  | Type   | Description                                                                                                                                                                      | Default                    | Allowed vals. |
|---------------------------------------|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------|---------------|
| ird.science_<br>dbi.outfilename       | string | The output filename for the product.<br>Please also see the esorex documentation for naming of output products.                                                                  | science_ dbi.fits          | -             |
| ird.science_ dbi.save_<br>addprod     | bool   | Flag signalling whether additional products should be saved. These are the individual, adi combined when required, products for the left and right fields                        | 1                          | -             |
| ird.science_ dbi.save_<br>interprod   | bool   | Flag signalling whether intermediate products should be saved/kept on disk. These are the prime starting points for independent differential analyses with third-party software! | 1                          | -             |
| ird.science_<br>dbi.outfilename_ left | string | The output filename for the product.<br>Please also see the esorex documentation for naming of output products.                                                                  | science_ dbi_<br>left.fits | -             |



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| Name                                | Type   | Description                                                                                                                                                                                                                                                                                                        | Default                | Allowed vals. |
|-------------------------------------|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|---------------|
| ird.science_dbi.make_template       | bool   | if set to TRUE the recipe creates an empty template of the field center table to be filled by hand.                                                                                                                                                                                                                | 0                      | -             |
| ird.science_dbi.outfilename_right   | string | The output filename for the product. Please also see the esorex documentation for naming of output products.                                                                                                                                                                                                       | science_dbi_right.fits | -             |
| ird.science_dbi.coll_alg            | int    | The collapse algorithm to use. 0 = Mean, 1 = Median.                                                                                                                                                                                                                                                               | 1                      | 0,1           |
| ird.science_dbi.use_adi             | bool   | Flag to control usage of ADI                                                                                                                                                                                                                                                                                       | 0                      | -             |
| ird.science_dbi.use_sdi             | bool   | Flag to control usage of SDI                                                                                                                                                                                                                                                                                       | 0                      | -             |
| ird.science_dbi.minr                | double | The minimum radius of the annulus used to renormalise the flux for SDI.                                                                                                                                                                                                                                            | 4.0                    | 0.0-512.0     |
| ird.science_dbi.maxr                | double | The maximum radius of the annulus used to renormalise the flux for SDI.                                                                                                                                                                                                                                            | 40.0                   | 0.0-512.0     |
| ird.science_dbi.full_frameset_speck | bool   | This sets whether speckle frames should be calculated per cube (if set to FALSE) or for the full set of frames (TRUE, default)                                                                                                                                                                                     | 1                      | -             |
| ird.science_dbi.transform_method    | int    | Transform method to use. 0 is FFT, 1 is CPL_WARP (interpolation).                                                                                                                                                                                                                                                  | 0                      | 0,1           |
| ird.science_dbi.filter_method       | int    | FFT filter method to use. 0 is none, 1 is top hat filter, 2 is Fermi filter, 3 is Butterworth filter.                                                                                                                                                                                                              | 0                      | 0,1,2,3       |
| ird.science_dbi.filter_rad          | double | Radius for FFT top hat and Fermi filters. A non zero value leads to suppression of high frequencies in the fourier domain before frame combination. The value expresses the minimum unsuppressed frequency as fraction of total frequency domain radius (a value of 1 would suppress essentially all frequencies). | 0.0                    | 0.0-1.0       |
| ird.science_dbi.fermi_temp          | double | The temperature parameter for the Fermi filter.                                                                                                                                                                                                                                                                    | 0.0                    | 0.0-1.0       |
| ird.science_dbi.butter_pass         | double | The pass band frequency for the Butterworth filter, as fraction of total frequency domain radius.                                                                                                                                                                                                                  | 0.0                    | 0.0-1.0       |
| ird.science_dbi.butter_stop         | double | The stop band frequency for the Butterworth filter, as fraction of total frequency domain radius. This must be larger than the pass frequency.                                                                                                                                                                     | 0.0                    | 0.0-1.0       |

| Name                                | Type   | Description                                                                                                                                                                                                                                                                                                                         | Default | Allowed vals. |
|-------------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ird.science_<br>dbi.window_<br>size | int    | When set to a non zero value, the recipe uses a special subwindow mode, where only cut-outs are of the given size are used (the cut out is made after dark and flat have been applied and the subfields have been extracted). For example to use only the central 128 pixels for both left and right subfields use window_size=128. | 0       | 0-1024        |
| ird.science_<br>dbi.star_<br>r      | double | The star radius [arcsecond] used for the Strehl ratio estimate. A negative value disables the estimation. This option is ignored in absence of a filter table frame.                                                                                                                                                                | 2.0     | -             |
| ird.science_<br>dbi.bg_<br>r1       | double | The internal radius [arcsecond] of the background used for the Strehl ratio estimate. This option is ignored in absence of a filter table frame.                                                                                                                                                                                    | 2.0     | -             |
| ird.science_<br>dbi.bg_<br>r2       | double | The external radius [arcsecond] of the background used for the Strehl ratio estimate. This option is ignored in absence of a filter table frame.                                                                                                                                                                                    | 3.0     | -             |

### 3.2.2.2.5 Description:

This recipe creates the reduced science frames for all science observations with IRDIS in DBI imaging mode. The recipe supports dithered frame combination, as well as ADI and SDI. The frames are reduced in the following steps:

1. The input raw frames are dark subtracted, see below
2. a flat field is divided out if it is provided
3. a badpixel map is created for each frame that contains the union of all dark and flat field badpixels \*\*\*(does not work)\*\*\*
4. the left and right IRDIS subframes are extracted using the IRDIS instrument model as specified in the header of the flat field (if provided) or the default model otherwise.

Now, for each of the subframes the processing is as follows:

1. high frequency filtering \*\*\*(switched off by default)\*\*\*. If the filter radius  $f_r$  is set to a value larger than 0, a top hat frequency filter is applied, masking out all frequencies above the value of  $f > f_r \times f_{max}$ , where  $f_{max}$  is the maximum frequency in the FFT. For noise filterings a value between 0.9 and 0.99 are good values to use for  $f_r$ .
2. FFT or warp shifting of image to recenter the image
3. Application of the distortion map to image
4. Shifting and distortion map application to badpixel map using geometrical approach

All these processed frames are then saved as temporary files. These are then combined to create a reference speckle image. Now the ADI or SDI steps are performed if one of them or both are selected. If not is selected, these steps are skipped.

1. The speckle frame is subtracted.
2. if SDI is selected, scaling of the images using FFT around the image center – the angle should be given as part of the field center table provided in the input of the recipe.
3. if ADI is selected, rotation of the images using FFT around the image center – the angle should be given as part of the field center table provided in the input of the recipe.

If the angles are not specified by the field center table, and ADI is turned on, the images will be aligned by rotating them all to a parallactic angle of zero. Then these frames are combined using the selected combination algorithm.

- if a weighted mean is selected, a weightmap is calculated first taking the median frame as a reference frame and weighing down the other frames depending on the difference in values. Note that this is still a very experimental option and it is still to be defined what weighting scheme would be optimal. All badpixels get assigned the weight of 0. Frames are then combined taking the individual weights into account.
- if a mean is selected, frames are combined using a mean, after first rejecting all bad pixels.
- if a median is selected, frames are combined by taking the median pixel value at each pixel position. This procedure ignores the badpixels.

The obtained combined results for the left and right IRDIS field of view are saved in a single FITS file with 8 extensions, following the layout for a double master frame: the first four extensions being the image, badpixelmap, N map, and rms for the left field and the second set of four extensions being the equivalent for the right field. Some additional notes:

- The static badpixel frame is optional and the badpixels defined there will be combined (using a logical OR) with badpixels in the dark or flat.
- Before the images are transformed (rotated and/or shifted) badpixels are interpolated. Interpolation happens irrespective of algorithm choice. The interpolation is a simple 8 neighbour pixel average. In case a number of  $n < 8$  neighbour pixels are also bad,  $8 - n$  values are used. In case all neighbour pixels are bad, the interpolation simply copies the value from nearest non bad pixel.
- While a filter table is not strictly required, no scaling will be done if SDI is selected, leading to zero images.
- For a point-source an estimate of the Strehl ratio may be useful. The presence of a filter table frame will enable the estimation, which on failure will do nothing and on success will insert Strehl related QC parameters into each product header.

**Dark handling:** This recipe will not run without a supplied dark or background frame. Possible frames to be subtracted are SKY\_BG\_FIT, SKY\_BG, INS\_BG\_FIT, INS\_BG, and MASTER\_DARK. DIT and readout mode should match the science data, but this is not verified by the recipe! For everything except MASTER\_DARK, it is a wise idea to also match the filter configuration! If you provide more than one of the optional frames, a choice will be made according to the following prioritization:

1. If a SKY\_BG\_FIT is available, this one is chosen.
2. Else if a SKY\_BG is available, this one is chosen.
3. Else if an INS\_BG\_FIT is available, this one is chosen.

4. Else if an INS\_BG is available, this one is chosen.
5. Else if a MASTER\_DARK is available, this one is chosen.
6. Else an error will be thrown and execution terminated.

#### 3.2.2.2.6 Products:

| Name              | Type        | Description                                                                                                                                                                                                                                                     |
|-------------------|-------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IRD_ SCIENCE_ DBI | FITS[Im(4)] | The main science frame. The FITS file contains 4 extensions: the image, the badpixels, the rms error and a weightmap for the total or difference of the left and right fields of view. Optionally, left and right field can be produced as additional products. |

### 3.2.3 IRDIS Classical Imaging (CI) Specific Calibrations and Science

#### 3.2.3.1 sph\_ird\_science\_imaging

##### 3.2.3.1.1 Purpose:

Science calibration, imaging mode.

##### 3.2.3.1.2 Input frames:

| Data Type (TAG)            | Source      | Optional | Min | Max |
|----------------------------|-------------|----------|-----|-----|
| IRD_ SCIENCE_ IMAGING_ RAW | Raw data    | No       | 1   | 500 |
| IRD_ MASTER_ DARK          | Calibration | Yes      | 0   | 1   |
| IRD_ INS_ BG               | Calibration | Yes      | 0   | 1   |
| IRD_ INS_ BG_ FIT          | Calibration | Yes      | 0   | 1   |
| IRD_ SKY_ BG               | Calibration | Yes      | 0   | 1   |
| IRD_ SKY_ BG_ FIT          | Calibration | Yes      | 0   | 1   |
| IRD_ FLAT_ FIELD           | Calibration | Yes      | 0   | 1   |
| IRD_ DISTORTION_ MAP       | Calibration | Yes      | 0   | 1   |
| IRD_ STAR_ CENTER          | Calibration | Yes      | 0   | 1   |
| IRD_ FCTABLE               | Calibration | Yes      | 0   | Any |
| IRD_ STATIC_ BADPIXELMAP   | Calibration | Yes      | 0   | 1   |
| IRD_ FILTER_ TABLE         | Calibration | Yes      | 0   | 1   |
| IRD_ PHOT_ STAR_ TABLE     | Calibration | Yes      | 0   | 1   |

##### 3.2.3.1.3 Raw frame keywords used:

| Keyword             | Type   | Optional | Description                                                          |
|---------------------|--------|----------|----------------------------------------------------------------------|
| ESO INS1 PAC X      | double | No       | The dithering position in X for the frame in pixels.                 |
| ESO INS1 PAC Y      | double | No       | The dithering position in Y for the frame in pixels.                 |
| ESO INS CPRT POSANG | double | Yes      | The rotation angle of frame in degrees. Only needed if ADI selected. |

##### 3.2.3.1.4 Parameters:



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| Name                                             | Type   | Description                                                                                                                                                                                                                                                                                                        | Default                         | Allowed vals. |
|--------------------------------------------------|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------|
| ird.science_<br>imaging.outfilename              | string | The output filename for the product.<br>Please also see the esorex documentation for naming of output products.                                                                                                                                                                                                    | science_<br>imaging.fits        | -             |
| ird.science_<br>imaging.outfilename_<br>left     | string | The output filename for the product.<br>Please also see the esorex documentation for naming of output products.                                                                                                                                                                                                    | science_ imaging_<br>left.fits  | -             |
| ird.science_<br>imaging.outfilename_<br>right    | string | The output filename for the product.<br>Please also see the esorex documentation for naming of output products.                                                                                                                                                                                                    | science_ imaging_<br>right.fits | -             |
| ird.science_<br>imaging.coll_ alg                | int    | The collapse algorithm to use. 0 = Mean, 1 = Median.                                                                                                                                                                                                                                                               | 1                               | 0,1           |
| ird.science_<br>imaging.keep_ fctable            | bool   | if set to TRUE the recipes internall created field center tables are not deleted.                                                                                                                                                                                                                                  | 0                               | -             |
| ird.science_<br>imaging.save_ addprod            | bool   | if set to TRUE the recipe will save additional products (left and write fields, in this case!)                                                                                                                                                                                                                     | 0                               | -             |
| ird.science_<br>imaging.use_ adi                 | bool   | Flag to control usage of ADI.                                                                                                                                                                                                                                                                                      | 0                               | -             |
| ird.science_<br>imaging.full_<br>frameset_ speck | bool   | This sets whether speckle frames should be calculated per cube (if set to FALSE) or for the full set of frames (TRUE, default)                                                                                                                                                                                     | 1                               | -             |
| ird.science_<br>imaging.transform_<br>method     | int    | Transform method to use. 0 is FFT, 1 is CPL_ WARP (interpolation).                                                                                                                                                                                                                                                 | 0                               | 0,1           |
| ird.science_<br>imaging.filter_ method           | int    | FFT filter method to use. 0 is none, 1 is top hat filter, 2 is Fermi filter, 3 is Butterworth filter.                                                                                                                                                                                                              | 0                               | 0,1,2,3       |
| ird.science_<br>imaging.filter_ rad              | double | Radius for FFT top hat and Fermi filters. A non zero value leads to suppression of high frequencies in the fourier domain before frame combination. The value expresses the minimum unsuppressed frequency as fraction of total frequency domain radius (a value of 1 would suppress essentially all frequencies). | 0.0                             | 0.0-1.0       |
| ird.science_<br>imaging.fermi_ temp              | double | The temperature parameter for the Fermi filter.                                                                                                                                                                                                                                                                    | 0.0                             | 0.0-1.0       |
| ird.science_<br>imaging.butter_ pass             | double | The pass band frequency for the Butterworth filter, as fraction of total frequency domain radius.                                                                                                                                                                                                                  | 0.0                             | 0.0-1.0       |
| ird.science_<br>imaging.butter_ stop             | double | The stop band frequency for the Butterworth filter, as fraction of total frequency domain radius. This must be larger than the pass frequency.                                                                                                                                                                     | 0.0                             | 0.0-1.0       |

| Name                       | Type   | Description                                                                                                                                                                                                                                                                                                                       | Default | Allowed vals. |
|----------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ird.science_imaging.star_r | double | The star radius [arcsecond] used for the Strehl ratio estimate. A negative value disables the estimation. When AO is enabled and 0 (default) is provided 2 arcseconds are used. When AO is disabled and 0 is provided a radius corresponding to 277 PIXEL is used. This option is ignored in absence of a IRD_FILTER_TABLE frame. | 0.0     | -             |
| ird.science_imaging.bg_r1  | double | The internal radius [arcsecond] of the background used for the Strehl ratio estimate. When AO is enabled and 0 (default) is provided 2 arcseconds are used. When AO is disabled and 0 is provided a radius corresponding to 277 PIXEL is used. This option is ignored in absence of a IRD_FILTER_TABLE frame.                     | 0.0     | -             |
| ird.science_imaging.bg_r2  | double | The external radius [arcsecond] of the background used for the Strehl ratio estimate. When AO is enabled and 0 (default) is provided 3 arcseconds are used. When AO is disabled and 0 is provided a radius corresponding to all the PIXELS in the image is used. This option is ignored in absence of a IRD_FILTER_TABLE frame.   | 0.0     | -             |

### 3.2.3.1.5 Description:

This recipe creates the reduced science frames for all science observations with IRDIS in classical imaging mode. The recipe supports dithered frame combination, but does not currently support any frame de-rotation. Use the **\*\*\*sph\_ird\_science\_dbi\*\*\*** recipe for cases when de-rotation is needed. The frames are reduced in the following steps:

1. The input raw frames are dark subtracted, see below
2. a flat field is divided out if it is provided
3. a badpixel map is created for each frame that contains the union of all dark and flat field badpixels **\*\*\*(does not work)\*\*\***
4. the left and right IRDIS subframes are extracted using the IRDIS instrument model as specified in the header of the flat field (if provided) or the default model otherwise.

Now, for each of the subframes the processing is as follows:

1. high frequency filtering **\*\*\*(switched off by default)\*\*\***. If the filter radius  $f_r$  is set to a value larger than 0, a top hat frequency filter is applied, masking out all frequencies above the value of  $f > f_r \times f_{max}$ , where  $f_{max}$  is the maximum frequency in the FFT. For noise filterings a value between 0.9 and 0.99 are good values to use for  $f_r$ .
2. FFT shifting of image to recenter the image

3. Application of the distortion map to image
4. Shifting and distortion map application to badpixel map using geometrical approach

All these processed frames are then saved as temporary files. Then these frames are combined using the selected combination algorithm.

- if a weighted mean is selected, a weightmap is calculated first taking the median frame as a reference frame and weighing down the other frames depending on the difference in values. Note that this is still a very experimental option and it is still to be defined what weighting scheme would be optimal. All badpixels get assigned the weight of 0. Frames are then combined taking the individual weights into account.
- if a mean is selected, frames are combined using a mean, after first rejecting all bad pixels.
- if a median is selected, frames are combined by taking the median pixel value at each pixel position. This procedure ignores the badpixels.

The obtained combined results for the left and right IRDIS field of view are saved in a single FITS file with 8 extensions, following the layout for a double master frame: the first four extensions being the image, badpixelmap, N map, and rms for the left field and the second set of four extensions being the equivalent for the right field. Some additional notes:

- For a point-source an estimate of the Strehl ratio may be useful. The presence of a filter table frame will enable the estimation, which on failure will do nothing and on success will insert Strehl related QC parameters into each product header.
- If additionally a standard star table is supplied and the target observed can be found in that table, an estimate of the zeropoint is also computed.

**Dark handling:** This recipe will not run without a supplied dark or background frame. Possible frames to be subtracted are SKY\_BG\_FIT, SKY\_BG, INS\_BG\_FIT, INS\_BG, and MASTER\_DARK. DIT and readout mode should match the science data, but this is not verified by the recipe! For everything except MASTER\_DARK, it is a wise idea to also match the filter configuration! **Strehl Ratio Calculation:** The recipe calculates the Strehl Ratio following these steps:

1. Optionally correct the residual local sky background evaluated in an annular region centered on the expected peak of the Point Spread Function (PSF). The region extends between bg\_r1 and bg\_r2. The center is the centroid of the apertures found in the image.
2. The PSF is identified and its integrated flux is normalized to 1. The flux is integrated in a circular region having radius star\_r;
3. The PSF barycentre is computed and used to generate the theoretical normalised PSF. It depends on the pixel scale (PIXSCAL extracted from the raw header) and on the nominal filter wavelength extracted from SPH\_IRD\_TAG\_FILTER\_TABLE\_CALIB;
4. The Strehl Ratio is the ratio between the maximum intensities of the PSF and the theoretical PSF.

**Zeropoint Calculation:** The recipe calculates the Zeropoint following these steps:

1. The zeropoint calculation uses the integrated flux ( $f$ ) of the star determined as part of the Strehl Ratio computation;

2. The standard star magnitude ( $m$ ) is extracted from SPH\_IRD\_TAG\_PHOT\_TABLE\_CALIB according to the filter employed;
3. The exposure time ( $t$ ) is extracted from the raw header;
4. The zeropoint is calculated as:

$$z = m + 2.5 * \log 10(f/t) \quad (3.1)$$

5. The zeropoint  $z$  is corrected by a correction factor  $c$  extracted from the appropriate extension of SPH\_IRD\_TAG\_FILTER\_TABLE\_CALIB:

$$z_c = z - c \quad (3.2)$$

6. Both  $z$  and  $z_c$  are written in the output products as QC parameters, e.g. for the left field we have ESO QC ZPOINT LEFT and ESO QC ZPOINTCORR LEFT respectively;

If you provide more than one of the optional frames, a choice will be made according to the following prioritization:

1. If a SKY\_BG\_FIT is available, this one is chosen.
2. Else if a SKY\_BG is available, this one is chosen.
3. Else if an INS\_BG\_FIT is available, this one is chosen.
4. Else if an INS\_BG is available, this one is chosen.
5. Else if a MASTER\_DARK is available, this one is chosen.
6. Else an error will be thrown and execution terminated.

### 3.2.3.1.6 Products:

| Name                | Type        | Description                                                                                                                                        |
|---------------------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
| IRD_SCIENCE_IMAGING | FITS[Im(4)] | The main science frame. The FITS file contains 4 extensions: the image, the badpixels, the rms error and a weightmap. All show the whole detector. |

## 3.2.4 IRDIS Long-Slit Spectroscopy (LSS) Specific Calibrations and Science

### 3.2.4.1 sph\_ird\_wave\_calib

#### 3.2.4.1.1 Purpose:

Perform the wavelength calibration

#### 3.2.4.1.2 Input frames:

| Data Type (TAG)        | Source      | Optional | Min | Max |
|------------------------|-------------|----------|-----|-----|
| IRD_WAVECALIB_RAW      | Raw data    | No       | 1   | 500 |
| IRD_INSTR_BG_RAW       | Raw data    | Yes      | 0   | 1   |
| IRD_FLAT_FIELD         | Calibration | No       | 1   | 1   |
| IRD_MASTER_DARK        | Calibration | Yes      | 0   | 1   |
| IRD_STATIC_BADPIXELMAP | Calibration | Yes      | 0   | 1   |

### 3.2.4.1.3 Raw frame keywords used:

none

### 3.2.4.1.4 Parameters:

| Name                                              | Type   | Description                                                                                                                                                                                                                                                                                                                                                                                                 | Default                     | Allowed vals. |
|---------------------------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|---------------|
| ird.wave_<br>calib.outfilename                    | string | The output filename for the product. Please also see the esorex documentation for naming of output products. ird.                                                                                                                                                                                                                                                                                           | irdis_<br>wave_<br>cal.fits | -             |
| ird.wave_<br>calib.coll_<br>alg                   | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean.                                                                                                                                                                                                                                                                                                                                        | 2                           | 0,1,2         |
| ird.wave_<br>calib.use_<br>inskeys                | bool   | Flag to set whether wavelengths should be set from INS keywords (ignoring then the user command line wavelength parameters).                                                                                                                                                                                                                                                                                | 0                           | -             |
| ird.wave_<br>calib.clean_<br>mean.reject_<br>high | int    | The clean mean reject pixels on high end.                                                                                                                                                                                                                                                                                                                                                                   | 0                           | 0-20          |
| ird.wave_<br>calib.clean_<br>mean.reject_<br>low  | int    | The clean mean reject pixels on low end.                                                                                                                                                                                                                                                                                                                                                                    | 0                           | 0-20          |
| ird.wave_<br>calib.threshold                      | double | Threshold for line detection. This value is used for line detection to determine a rough estimate of dispersion and the line positions before the more careful wavelength calibration is done. The value here should be between the background and the maximal value of the faintest line visible on the image. If the value is negative (default), the threshold is set to ten times the image mean value. | 1000.0                      | -             |
| ird.wave_<br>calib.smooth                         | double | When set to a positive value, the raw input data is smoothed with a gauss of the given FWHM before lines are detected and peaks determined.                                                                                                                                                                                                                                                                 | 0.0                         | -             |
| ird.wave_<br>calib.wavelength_<br>line1           | double | The wavelength of first line [nm].                                                                                                                                                                                                                                                                                                                                                                          | 987.72                      | -             |
| ird.wave_<br>calib.wavelength_<br>line2           | double | The wavelength of second line [nm].                                                                                                                                                                                                                                                                                                                                                                         | 1123.71                     | -             |
| ird.wave_<br>calib.wavelength_<br>line3           | double | The wavelength of third line [nm].                                                                                                                                                                                                                                                                                                                                                                          | 1309.0                      | -             |
| ird.wave_<br>calib.wavelength_<br>line4           | double | The wavelength of fourth line [nm].                                                                                                                                                                                                                                                                                                                                                                         | 1545.07                     | -             |
| ird.wave_<br>calib.wavelength_<br>line5           | double | The wavelength of fifth line [nm].                                                                                                                                                                                                                                                                                                                                                                          | 1730.23                     | -             |
| ird.wave_<br>calib.wavelength_<br>line6           | double | The wavelength of sixth line [nm].                                                                                                                                                                                                                                                                                                                                                                          | 2015.33                     | -             |
| ird.wave_<br>calib.line_<br>tolerance             | int    | The maximal pixel tolerance around which lines are searched for peaks in exposure.                                                                                                                                                                                                                                                                                                                          | 5                           | -             |

| Name                             | Type   | Description                                                                                                                                                                                                                                                                          | Default | Allowed vals. |
|----------------------------------|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ird.wave_<br>calib.number_ lines | int    | The number of lines to use. Any input wavelength value for lines with a number higher than the total number of lines to use are ignored.                                                                                                                                             | 6       | 2-6           |
| ird.wave_ calib.degree           | int    | The polynomial degree to use for the fitting. This should always be at most one less than the number of lines used.                                                                                                                                                                  | 3       | 1-6           |
| ird.wave_<br>calib.column_ width | int    | The width of the sliding window used to average pixels together before the wavelength solution is found.                                                                                                                                                                             | 200     | -             |
| ird.wave_ calib.grism_<br>mode   | string | Switch between grism mode (TRUE), prism mode (FALSE), or automatic (AUTO). In auto mode, the ESO.INS1.OPT11.NAME keyword determines the mode, whether grism or prism. In grism mode the fitting coefficients $c2 = c3 = c4 = 0$ , and the corresponding user parameters are ignored. | AUTO    | -             |
| ird.wave_ calib.c2               | double | The c2 coefficient in the fit                                                                                                                                                                                                                                                        | -43.352 | -             |
| ird.wave_ calib.c3               | double | The c3 coefficient in the fit                                                                                                                                                                                                                                                        | 149.723 | -             |
| ird.wave_ calib.c4               | double | The c4 coefficient in the fit                                                                                                                                                                                                                                                        | 82.442  | -             |

#### 3.2.4.1.5 Description:

This recipe performs the wavelength calibration. The raw frames are combined, dark subtracted and flat fielded, flagging any badpixels in the process. After combining the raw frames, the recipe will attempt to detect the lines. For this purpose, the image is sliced into lines parallel to the wavelength direction. For each slice, peaks belonging to the calibration wavelengths are found and assigned to the corresponding input wavelengths. This is done for each calibration wavelength by searching a window region of  $\pm$  ird.wave\_calib.line\_tolerance around the expected pixel for the peak of the calibration wavelength (assuming a linear dispersion and the minimum and maximum wavelengths as specified in the header of the master instrument flat field frame) for the maximum image value. The actual positions for all input calibration lines are stored and a polynomial fit of input calibration lines versus actual pixel positions is performed and used to interpolate all wavelength values between calibration lines for the image slice. Once all slices inside the spectral region have been processed the PDT is updated with the new information and written out as the product.

#### 3.2.4.1.6 Products:

| Name | Type | Description |
|------|------|-------------|
|------|------|-------------|

| Name           | Type        | Description                                                                                                                                                                                                                                                                                                                                                                                                                                             |
|----------------|-------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IRD_ WAVECALIB | FITS[Im(9)] | The wavelength calibration data. This FITS file contains in total six extensions, all containing imaging data. Each image corresponds to one column in the pixel description table (PDT). The order is: wavelength, spectra id, slit id, wavelength width (or error on wavelength), second derivative and illumination fraction. . Additionally saved is the image resulting from a simple combination of all frames, the bad pixel map and an RMS map. |

### 3.2.4.2 sph\_ird\_science\_spectroscopy

#### 3.2.4.2.1 Purpose:

Science calibration, spectroscopy mode.

#### 3.2.4.2.2 Input frames:

| Data Type (TAG)                 | Source      | Optional | Min | Max |
|---------------------------------|-------------|----------|-----|-----|
| IRD_ SCIENCE_ SPECTROSCOPY_ RAW | Raw data    | No       | 1   | 500 |
| IRD_ MASTER_ DARK               | Calibration | Yes      | 0   | 1   |
| IRD_ INS_ BG                    | Calibration | Yes      | 0   | 1   |
| IRD_ INS_ BG_ FIT               | Calibration | Yes      | 0   | 1   |
| IRD_ SKY_ BG                    | Calibration | Yes      | 0   | 1   |
| IRD_ SKY_ BG_ FIT               | Calibration | Yes      | 0   | 1   |
| IRD_ FLAT_ FIELD                | Calibration | No       | 1   | 1   |
| IRD_ ATMOSPHERIC                | Calibration | Yes      | 0   | 1   |
| IRD_ STATIC_ BADPIXELMAP        | Calibration | Yes      | 0   | 1   |

#### 3.2.4.2.3 Raw frame keywords used:

none

#### 3.2.4.2.4 Parameters:

| Name                                  | Type   | Description                                                                                                  | Default                    | Allowed vals. |
|---------------------------------------|--------|--------------------------------------------------------------------------------------------------------------|----------------------------|---------------|
| ird.science_ spectroscopy.outfilename | string | The output filename for the product. Please also see the esorex documentation for naming of output products. | science_ spectroscopy.fits | -             |
| ird.science_ spectroscopy.coll_ alg   | int    | The collapse algorithm to use. 0 = Mean, 1 = Median.                                                         | 0                          | 0,1           |

#### 3.2.4.2.5 Description:

This recipe creates the actual science frames for spectroscopy mode. In spectroscopy mode, frames are not dithered and so this recipe performs a simple processing of dark subtraction and flat fielding before using a user specified method to combine the frames. If a atmospheric calibration is provided this is subtracted from the result.

### 3.2.4.2.6 Known Issues:

The recipe is not using the wavelength calibration file. In order to remove the effects of the wavelength dependence of the flat, the recipe should really use a series of flats taken at different wavelengths and construct a 'super' flat from this using the wavelength calibration file, in the same way as this is done for IFS. However, it is not clear if this is in fact required or if the wavelength dependence of the flat has too small an effect on the spectroscopic data reduction to make it necessary to perform this wavelength dependent calibration.

### 3.2.4.2.7 Products:

| Name                              | Type        | Description                                                                                                                                                                                                                                                          |
|-----------------------------------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IRD_ SCIENCE_ SPECTROSCOPY_ LEFT  | FITS[Im(4)] | The reduced spectroscopy frame of the left FOV. This frame contains a full detector image with the 2D spectrum. The format is FITS with 4 extensions, the actual image data, the badpixels, the ncombmap (how many frames contributed to each pixel), and a RMS map. |
| IRD_ SCIENCE_ SPECTROSCOPY_ RIGHT | FITS[Im(4)] | Same as the above, but for the right FOV                                                                                                                                                                                                                             |

## 3.2.5 IRDIS Dual-Band Polarimetry (DPI) Specific Calibrations and Science

### 3.2.5.1 sph\_ird\_science\_dpi

#### 3.2.5.1.1 Purpose:

Science calibration, DPI mode.

#### 3.2.5.1.2 Input frames:

| Data Type (TAG)          | Source      | Optional | Min | Max |
|--------------------------|-------------|----------|-----|-----|
| IRD_ SCIENCE_ DPI_ RAW   | Raw data    | No       | 1   | Any |
| IRD_ MASTER_ DARK        | Calibration | Yes      | 0   | 1   |
| IRD_ INS_ BG             | Calibration | Yes      | 0   | 1   |
| IRD_ INS_ BG_ FIT        | Calibration | Yes      | 0   | 1   |
| IRD_ SKY_ BG             | Calibration | Yes      | 0   | 1   |
| IRD_ SKY_ BG_ FIT        | Calibration | Yes      | 0   | 1   |
| IRD_ FLAT_ FIELD         | Calibration | No       | 1   | 1   |
| IRD_ DISTORTION_ MAP     | Calibration | Yes      | 0   | 1   |
| IRD_ STAR_ CENTER        | Calibration | Yes      | 0   | 1   |
| IRD_ FCTABLE             | Calibration | Yes      | 0   | Any |
| IRD_ STATIC_ BADPIXELMAP | Calibration | Yes      | 0   | 1   |

#### 3.2.5.1.3 Raw frame keywords used:

none

### 3.2.5.1.4 Parameters:

| Name                                            | Type   | Description                                                                                                                                                                                                                                                                                                        | Default                        | Allowed vals. |
|-------------------------------------------------|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|---------------|
| ird.science_<br>dpi.outfilename                 | string | The output filename for the product.<br>Please also see the esorex documentation for naming of output products.                                                                                                                                                                                                    | science_<br>dpi.fits           | -             |
| ird.science_<br>dpi.save_<br>addprod            | bool   | Flag signalling whether additional products should be saved. These are the individual, adi combined when required, products for the left and right fields                                                                                                                                                          | 1                              | -             |
| ird.science_<br>dpi.save_<br>interprod          | bool   | Flag signalling whether intermediate products should be saved/kept on disk. These are the prime starting points for independent differential analyses with third-party software!                                                                                                                                   | 1                              | -             |
| ird.science_<br>dpi.outfilename_<br>left        | string | The output filename for the product.<br>Please also see the esorex documentation for naming of output products.                                                                                                                                                                                                    | science_<br>dpi_<br>left.fits  | -             |
| ird.science_<br>dpi.outfilename_<br>right       | string | The output filename for the product.<br>Please also see the esorex documentation for naming of output products.                                                                                                                                                                                                    | science_<br>dpi_<br>right.fits | -             |
| ird.science_<br>dpi.coll_<br>alg                | int    | The collapse algorithm to use. 0 = Mean, 1 = Median.                                                                                                                                                                                                                                                               | 1                              | 0,1           |
| ird.science_<br>dpi.use_<br>adi                 | bool   | Flag to control usage of ADI                                                                                                                                                                                                                                                                                       | 0                              | -             |
| ird.science_<br>dpi.use_<br>sdi                 | bool   | Flag to control usage of SDI                                                                                                                                                                                                                                                                                       | 0                              | -             |
| ird.science_<br>dpi.keep_<br>fctable            | bool   | Has no effect. Use the save_interprod option instead.                                                                                                                                                                                                                                                              | 0                              | -             |
| ird.science_<br>dpi.minr                        | double | The minimum radius of the annulus used to renormalise the flux for SDI.                                                                                                                                                                                                                                            | 4.0                            | 0.0-512.0     |
| ird.science_<br>dpi.maxr                        | double | The maximum radius of the annulus used to renormalise the flux for SDI.                                                                                                                                                                                                                                            | 40.0                           | 0.0-512.0     |
| ird.science_<br>dpi.full_<br>frameset_<br>speck | bool   | This sets whether speckle frames should be calculated per cube (if set to FALSE) or for the full set of frames (TRUE, default)                                                                                                                                                                                     | 1                              | -             |
| ird.science_<br>dpi.transform_<br>method        | int    | Transform method to use. 0 is FFT, 1 is CPL_WARP (interpolation).                                                                                                                                                                                                                                                  | 0                              | 0,1           |
| ird.science_<br>dpi.filter_<br>method           | int    | FFT filter method to use. 0 is none, 1 is top hat filter, 2 is Fermi filter, 3 is Butterworth filter.                                                                                                                                                                                                              | 0                              | 0,1,2,3       |
| ird.science_<br>dpi.filter_<br>rad              | double | Radius for FFT top hat and Fermi filters. A non zero value leads to suppression of high frequencies in the fourier domain before frame combination. The value expresses the minimum unsuppressed frequency as fraction of total frequency domain radius (a value of 1 would suppress essentially all frequencies). | 0.0                            | 0.0-1.0       |

| Name                                | Type   | Description                                                                                                                                    | Default | Allowed vals. |
|-------------------------------------|--------|------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ird.science_<br>dpi.fermi_<br>temp  | double | The temperature parameter for the Fermi filter.                                                                                                | 0.0     | 0.0-1.0       |
| ird.science_<br>dpi.butter_<br>pass | double | The pass band frequency for the Butterworth filter, as fraction of total frequency domain radius.                                              | 0.0     | 0.0-1.0       |
| ird.science_<br>dpi.butter_<br>stop | double | The stop band frequency for the Butterworth filter, as fraction of total frequency domain radius. This must be larger than the pass frequency. | 0.0     | 0.0-1.0       |

#### 3.2.5.1.5 Description:

This recipe creates the reduced science frames for all science observations with IRDIS in DPI mode. The recipe is essentially identical to the DBI science recipe, except that the final result is saved as as I and P frames (rather than left and right field of views). Please see the description of the IRDIS DBI recipe for more details on the processing.

#### 3.2.5.1.6 Products:

| Name                | Type        | Description                                                                                                                                                                                                                                                                                                                                                            |
|---------------------|-------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IRD _ SCIENCE _ DPI | FITS[Im(8)] | The main science frame. The FITS file contains 8 extensions: the first 4 extensions contain the polarization (P) image, the badpixels, the rms error and a weightmap of the polarisation. The last 4 extensions contain the same information for the intensity (I) image. Note that when ADI is requested, only 4 extensions are present, containing only the P image. |

### 3.2.6 IRDIS Advanced Recipes for Differential Imaging

These recipes are currently being kept for future use but are not actively maintained. They should not be used in the present version and will most probably not work anyway.

#### 3.2.6.1 sph\_ird\_andromeda

##### 3.2.6.1.1 Purpose:

Andromeda recipe.

### 3.2.6.1.2 Input frames:

| Data Type (TAG)          | Source      | Optional | Min | Max |
|--------------------------|-------------|----------|-----|-----|
| IRD_ ANDROMEDA_ RAW      | Raw data    | No       | 1   | Any |
| IRD_ MASTER_ DARK        | Calibration | No       | 1   | 1   |
| IRD_ FLAT_ FIELD         | Calibration | No       | 1   | 1   |
| IRD_ DISTORTION_ MAP     | Calibration | Yes      | 0   | 1   |
| IRD_ STAR_ CENTER        | Calibration | Yes      | 0   | 1   |
| IRD_ FCTABLE             | Calibration | Yes      | 0   | Any |
| IRD_ FILTER_ TABLE       | Calibration | Yes      | 0   | 1   |
| IRD_ PSF_ REFERENCE      | Calibration | No       | 1   | 1   |
| IRD_ STATIC_ BADPIXELMAP | Calibration | Yes      | 0   | 1   |

### 3.2.6.1.3 Raw frame keywords used:

| Keyword                              | Type   | Optional | Description                                                                  |
|--------------------------------------|--------|----------|------------------------------------------------------------------------------|
| ESO DRS IRD DUAL FILTER LAMBDA LEFT  | double | Yes      | The central wavelength of the filter on left. Only needed if SDI requested.  |
| ESO DRS IRD DUAL FILTER LAMBDA RIGHT | double | Yes      | The central wavelength of the filter on right. Only needed if SDI requested. |
| ESO INS1 PAC X                       | double | No       | The dithering position in X for the frame in pixels.                         |
| ESO INS1 PAC Y                       | double | No       | The dithering position in Y for the frame in pixels.                         |
| ESO INS CPRT POSANG                  | double | Yes      | The rotation angle of frame in degrees.                                      |

### 3.2.6.1.4 Parameters:

| Name                                 | Type   | Description                                                                                                                                                            | Default         | Allowed vals. |
|--------------------------------------|--------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|---------------|
| ird.andromeda.outfilename            | string | The output filename for the product. Please also see the esorex documentation for naming of output products.                                                           | andromeda.fits  | -             |
| ird.andromeda.left_filename          | string | The output filename for the left list after pre-processing. Only used if only_prep flag is set. Please also see the esorex documentatio for naming of output products. | left_list.fits  | -             |
| ird.andromeda.right_filename         | string | The output filename for the left list after pre-processing. Only used if only_prep flag is set. Please also see the esorex documentatio for naming of output products. | right_list.fits | -             |
| ird.andromeda.keep_fctable           | bool   | if set to TRUE the recipes internall created field center tables are not deleted.                                                                                      | 0               | -             |
| ird.andromeda.coll_alg               | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean.                                                                                                   | 2               | 0,1,2         |
| ird.andromeda.clean_mean.reject_high | int    | The clean mean reject pixels on high end.                                                                                                                              | 1               | 0-20          |
| ird.andromeda.clean_mean.reject_low  | int    | The clean mean reject pixels on low end.                                                                                                                               | 1               | 0-20          |
| ird.andromeda.use_sdi                | bool   | Flag to control usage of SDI                                                                                                                                           | 0               | -             |

| Name                        | Type   | Description                                                                                                                                                                                                                                                                                                       | Default | Allowed vals. |
|-----------------------------|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ird.andromeda.window_minx   | int    | Window region andromeda is applied to.                                                                                                                                                                                                                                                                            | 428     | 0-1024        |
| ird.andromeda.window_miny   | int    | Window region andromeda is applied to.                                                                                                                                                                                                                                                                            | 428     | 0-1024        |
| ird.andromeda.window_maxx   | int    | Window region andromeda is applied to.                                                                                                                                                                                                                                                                            | 628     | 0-1024        |
| ird.andromeda.window_maxy   | int    | Window region andromeda is applied to.                                                                                                                                                                                                                                                                            | 628     | 0-1024        |
| ird.andromeda.psf_size      | int    | The size of the reference PSF. A central window of this size is extracted from the input PSF reference frame to create the PSF reference image to use by andromeda.                                                                                                                                               | 32      | 0-128         |
| ird.andromeda.only_prep     | bool   | Flag to switch off andromeda so only preparatory steps are performed: these are dark subtraction and flat fielding, frame cropping, frame centering and scaling (if SDI is on).                                                                                                                                   | 0       | -             |
| ird.andromeda.min_ang_sep   | double | The minimum angle separation to use to create the image pairs for image differencing.                                                                                                                                                                                                                             | 1.0     | 0.0-45.0      |
| ird.andromeda.rho_min       | double | The minimum radius to search for.                                                                                                                                                                                                                                                                                 | 1.0     | 0.0-200.0     |
| ird.andromeda.rho_max       | double | The maximum radius to search for.                                                                                                                                                                                                                                                                                 | 10.0    | 0.0-200.0     |
| ird.andromeda.filter_radius | double | Filter radius for ADI frame combination. A non zero value leads to suppression of high frequencies in the fourier domain before frame combination. The value expresses the minimum unsuppressed frequency as fraction of total frequency domain radius (a value of 1 would suppress essentially all frequencies). | 0.0     | 0.0-1.0       |

#### 3.2.6.1.5 Description:

This recipe uses the Andromeda algorithm (Mugnier et al. 2008) for planet detection. The recipe has been implemented in C following the IDL script obtained from L. Mugnier as much as possible. The basic reduction of raw frames follows that of the other IRDIS science recipes, in particular dark subtraction, flat fielding and frame centering is done as for the science\_dbi recipe. Please see the science\_dbi recipe for more details. Andromeda can also be used in combination with SDI by switching the use\_sdi flag to TRUE. The current version is only a first attempt – please use with care.

#### 3.2.6.1.6 Known Issues:

The recipe result is very sensitive to the input parameter choice and we believe this may indicate a bug somewhere. We also found that obtaining useful results on some input data is not possible.

#### 3.2.6.1.7 Products:

| Name           | Type        | Description                                                                                                                                        |
|----------------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
| IRD_ ANDROMEDA | FITS[Im(4)] | The main science frame. The FITS file contains 4 extensions: the image, the badpixels, the rms error and a weightmap. All show the whole detector. |

### 3.2.6.2 sph\_ird\_loci

#### 3.2.6.2.1 Purpose:

LOCI recipe.

#### 3.2.6.2.2 Input frames:

| Data Type (TAG)          | Source      | Optional | Min | Max |
|--------------------------|-------------|----------|-----|-----|
| IRD_ LOCI_ RAW           | Raw data    | No       | 1   | Any |
| IRD_ MASTER_ DARK        | Calibration | No       | 1   | 1   |
| IRD_ FLAT_ FIELD         | Calibration | No       | 1   | 1   |
| IRD_ DISTORTION_ MAP     | Calibration | Yes      | 0   | 1   |
| IRD_ STAR_ CENTER        | Calibration | Yes      | 0   | 1   |
| IRD_ FILTER_ TABLE       | Calibration | Yes      | 0   | 1   |
| IRD_ STATIC_ BADPIXELMAP | Calibration | Yes      | 0   | 1   |
| IRD_ FCTABLE             | Calibration | Yes      | 0   | Any |

#### 3.2.6.2.3 Raw frame keywords used:

| Keyword                              | Type   | Optional | Description                                                                  |
|--------------------------------------|--------|----------|------------------------------------------------------------------------------|
| ESO DRS IRD DUAL FILTER LAMBDA LEFT  | double | Yes      | The central wavelength of the filter on left. Only needed if SDI requested.  |
| ESO DRS IRD DUAL FILTER LAMBDA RIGHT | double | Yes      | The central wavelength of the filter on right. Only needed if SDI requested. |
| ESO INS1 PAC X                       | double | No       | The dithering position in X for the frame in pixels.                         |
| ESO INS1 PAC Y                       | double | No       | The dithering position in Y for the frame in pixels.                         |
| ESO INS CPRT POSANG                  | double | Yes      | The rotation angle of frame in degrees.                                      |

#### 3.2.6.2.4 Parameters:

| Name                     | Type   | Description                                                                                                                                                            | Default          | Allowed vals. |
|--------------------------|--------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|---------------|
| ird.loci.outfilename     | string | The output filename for the product. Please also see the esorex documentation for naming of output products.                                                           | loci.fits        | -             |
| ird.loci.left_ filename  | string | The output filename for the left list after pre-processing. Only used if only_prep flag is set. Please also see the esorex documentatio for naming of output products. | left_ list.fits  | -             |
| ird.loci.right_ filename | string | The output filename for the left list after pre-processing. Only used if only_prep flag is set. Please also see the esorex documentatio for naming of output products. | right_ list.fits | -             |

| Name                              | Type   | Description                                                                                                                                                                                                                                                                                                       | Default | Allowed vals. |
|-----------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ird.loci.keep_ fctable            | bool   | if set to TRUE the recipes internall created field center tables are not deleted.                                                                                                                                                                                                                                 | 0       | -             |
| ird.loci.coll_ alg                | int    | The collapse algorithm to use. 0 = Mean, 1 = Median.                                                                                                                                                                                                                                                              | 1       | 0,1           |
| ird.loci.clean_ mean.reject_ high | int    | The clean mean reject pixels on high end.                                                                                                                                                                                                                                                                         | 1       | 0-20          |
| ird.loci.clean_ mean.reject_ low  | int    | The clean mean reject pixels on low end.                                                                                                                                                                                                                                                                          | 1       | 0-20          |
| ird.loci.use_ sdi                 | bool   | Flag to control usage of SDI                                                                                                                                                                                                                                                                                      | 0       | -             |
| ird.loci.na                       | double | The LOCI Na parameter                                                                                                                                                                                                                                                                                             | 300.0   | 1.0-1000.0    |
| ird.loci.ndelta                   | double | The LOCI Ndelta parameter                                                                                                                                                                                                                                                                                         | 0.5     | 0.0-5.0       |
| ird.loci.w                        | double | The LOCI w parameter (usually size of PSF)                                                                                                                                                                                                                                                                        | 2.0     | 0.0-50.0      |
| ird.loci.g                        | double | The LOCI g parameter                                                                                                                                                                                                                                                                                              | 1.0     | 0.0-5.0       |
| ird.loci.minr                     | double | The minimum radius for the LOCI annulus                                                                                                                                                                                                                                                                           | 50.0    | 0.0-1000.0    |
| ird.loci.maxr                     | double | The maximum radius for the LOCI annulus                                                                                                                                                                                                                                                                           | 200.0   | 0.0-1000.0    |
| ird.loci.dr                       | double | The width of the segment annuli.                                                                                                                                                                                                                                                                                  | 5.0     | 1.0-100.0     |
| ird.loci.div_ scheme              | int    | The LOCI segment divisions scheme to use. 0 = NORMAL, 1 = FINE. .                                                                                                                                                                                                                                                 | 1       | 0,1           |
| ird.loci.filter_ radius           | double | Filter radius for ADI frame combination. A non zero value leads to suppression of high frequencies in the fourier domain before frame combination. The value expresses the minimum unsuppressed frequency as fraction of total frequency domain radius (a value of 1 would suppress essentially all frequencies). | 0.0     | 0.0-1.0       |

### 3.2.6.2.5 Description:

This is LOCI. LOCI is the >>locally optimized combination of images<< algorithm invented by Lafreniere and Marois. The SPHERE implementation follows the paper Lafraniere et al. (2007, ApJ, 660) very closely. Input parameters are named equivalently to the parameters as they appear in the paper. The preprocessing done before the actual LOCI algorithm is applied is the same as that for other IRDIS science recipes (e.g. science\_dbi): the raw frames are dark subtracted, flat fielded and centered. It is also possible to run SDI before LOCI, by setting the use\_sdi switch to TRUE. Please see the description for the science\_dbi recipe for more details on the basic reductions. LOCI itself is implemented as in the original paper without any special tweaks. The step of subtracting the radial profile before LOCI is run as described in the paper is currently not implemented. The final output of the recipe is a LOCI image – since no special care is taken for normalisation etc. beware any flux determinations from this image.

### 3.2.6.2.6 Known Issues:

No support for radial profile subtraction.

### 3.2.6.2.7 Products:

| Name     | Type        | Description                                                                                                                                        |
|----------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
| IRD_LOCI | FITS[Im(4)] | The main science frame. The FITS file contains 4 extensions: the image, the badpixels, the rms error and a weightmap. All show the whole detector. |

### 3.2.7 IRDIS Workflow Summary

The IRDIS workflow is summarized in Fig.3.3(initial part) and Fig.3.4(final part).

### 3.2.8 IRDIS Special notes

#### 3.2.8.1 The Instrument Model

Many IRDIS recipes list IRD\_INSTRUMENT\_MODEL frames as possible input. These are currently unavailable and the instrument model, a set of numbers that describe the positions and extents of the two FOVs on the IRDIS detector are usually stored in IRD\_FLAT\_FIELD frames produced by the sph\_ird\_instrument\_flat recipe. This is the reason why IRD\_FLAT\_FIELD frames are usually mandatory in all higher-order recipes.

#### 3.2.8.2 Dark and Background Calibration

Most IRDIS recipes accept several types of dark or background products for subtraction:

- IRD\_MASTER\_DARK
- IRD\_INS\_BG
- IRD\_INS\_BG\_FIT
- IRD\_SKY\_BG
- IRD\_SKY\_BG\_FIT

Some of the recipes require that at least one dark is provided, some run also without any dark or background frame. For details, look at the recipe descriptions in the subsections above or at the recipe man pages. If more than one dark / background frame are fed into a single recipe, the recipe will select one according to the following logic:

1. if IRD\_SKY\_BG\_FIT is provided, this one is chosen
2. else if IRD\_SKY\_BG is provided, this one is chosen
3. else if IRD\_INS\_BG\_FIT is provided, this one is chosen
4. else if IRD\_INS\_BG is provided, this one is chosen
5. else if IRD\_MASTER\_DARK is provided, this one is chosen
6. else an error is thrown, some recipes also continue without subtracting any dark or background.

Note that the else-if chain implies that all others are ignored after a choice has been made. For all dark/background products a pre-selection should be made by the user (or any automatic environment) to select only calibration products with the same DIT and readout mode. For everything except the IRD\_MASTER\_DARK frames, also the filter configuration should be matched!

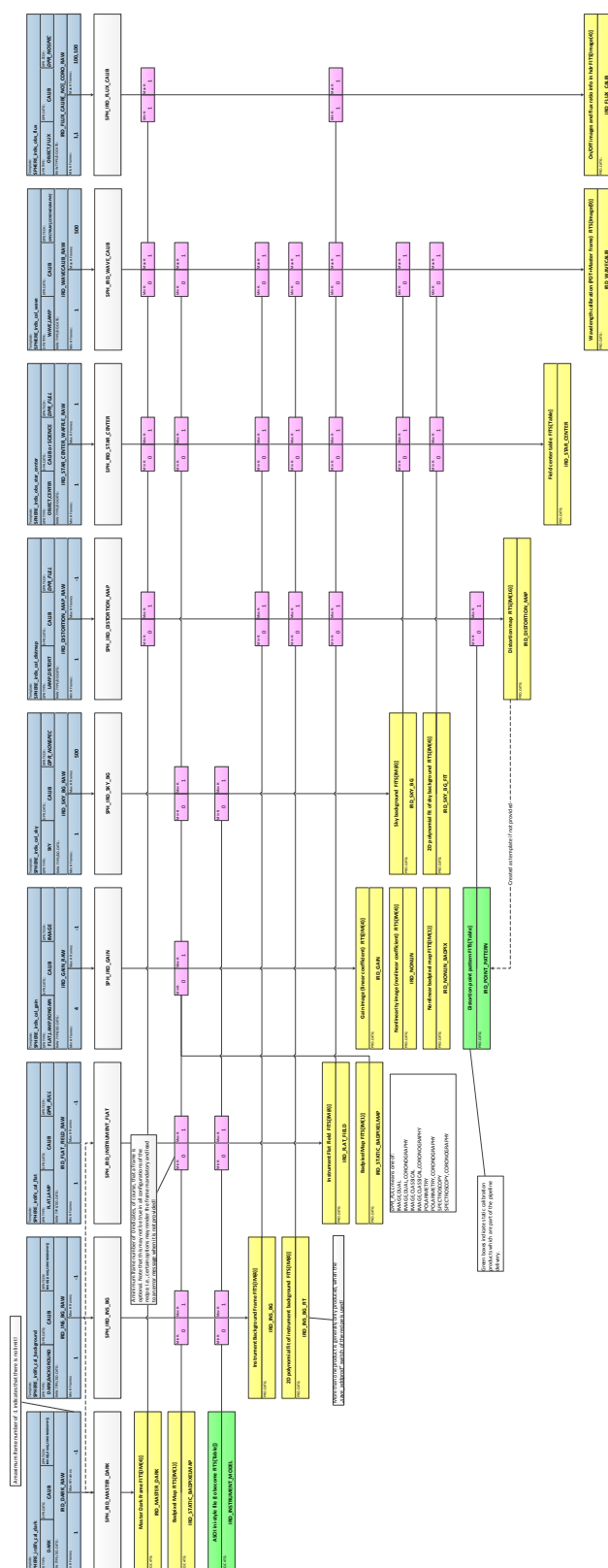


Figure 3.3: Initial part of the IRDIS calibration cascade (workflow).

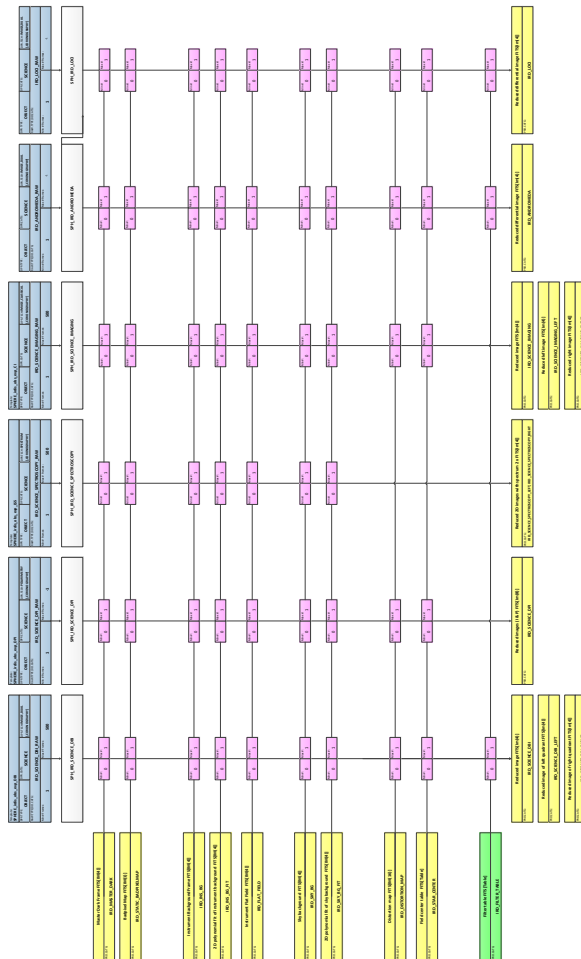


Figure 3.4: Final part of the IRDIS calibration cascade (workflow)

## 3.3 IFS

IFS offers two basic modes:

- YH
- YK

The calibration cascade (workflow) is identical for both modes. Care should however be taken that calibration products and raw frames always were taken in the same mode!

### 3.3.1 IFS Calibrations and Science

#### 3.3.1.1 sph\_ifs\_gain

##### 3.3.1.1.1 Purpose:

Measure the detector gain

##### 3.3.1.1.2 Input frames:

| Data Type (TAG) | Source   | Optional | Min | Max |
|-----------------|----------|----------|-----|-----|
| IFS_ GAIN_ RAW  | Raw data | No       | 4   | Any |

##### 3.3.1.1.3 Raw frame keywords used:

none

##### 3.3.1.1.4 Parameters:

| Name                              | Type   | Description                                                                                                                   | Default                | Allowed vals. |
|-----------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------------|------------------------|---------------|
| ifs.gain.outfilename              | string | The output filename for the product. Please also see the esorex documentation for naming of output products.                  | ifs_ gain_ map.fits    | -             |
| ifs.gain.nonlin_ filename         | string | The output filename for the nonlinearity map. Please also see the esorex documentation for naming of output products.         | ifs_ nonlin_ map.fits  | -             |
| ifs.gain.nonlin_ bpixname         | string | The output filename for the non linear bad pixel map. Please also see the esorex documentation for naming of output products. | ifs_ nonlin_ bpix.fits | -             |
| ifs.gain.coll_ alg                | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean.                                                          | 2                      | 0,1,2         |
| ifs.gain.clean_ mean.reject_ high | int    | The clean mean reject pixels on high end.                                                                                     | 0                      | 0-20          |
| ifs.gain.clean_ mean.reject_ low  | int    | The clean mean reject pixels on low end.                                                                                      | 0                      | 0-20          |
| ifs.gain.order                    | int    | The fitting order to use, can be 1 (for linear only) or 2 ( for lin+quadratic).                                               | 2                      | 1-2           |

| Name                    | Type   | Description                                                                                                                                                                                                                                             | Default | Allowed vals. |
|-------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ifs.gain.lin_ tolerance | double | The allowed maximum absolute value of the second order of the polynomial fit. Any pixels that have an absolute value for the second order polynomial coefficient above this value are considered non-linear and marked as bad in the non-linearity map. | 100.0   | -             |
| ifs.gain.preproc        | bool   | If set to TRUE, the raw frames are first processed to remove any offset trends within data cubes                                                                                                                                                        | 1       | -             |
| ifs.gain.vacca          | bool   | Choose the special noise calculation by Vacca et al. (2004) that takes the number of fowler samples into account.                                                                                                                                       | 0       | -             |

### 3.3.1.1.5 Description:

The gain recipe calculates the gain for the detector and derives a mask of nonlinear pixels. The input is assumed to be a series of data cubes, each containing a single extension with  $N > 3$  planes that each contain a single exposure. The mean count for each input cube should be different either by increasing the intensity of the illumination source or by using different exposure times. Note that in the latter case the recipe only produces the correct output if the detector gain is independent of the read out mode. The gain recipe, as well as the ron recipe, have a special optional preprocessing step, which corrects some possible bias due to readout electronics settings by first subtracting the median of each input cube from each image in the cube. The gain recipe offers algorithms to calculate the gain, one straightforward fitting algorithm and a more complex fitting algorithm that takes the correct number of fowler samples into account. The second algorithm is switched on using the vacca user parameter and is preferable for accurate gain determinations but can currently not be used to calculate the detector non-linearity. It is therefore recommended to set the user parameter vacca to 1 when an accurate gain measurement is needed but not non-linearity measurement is needed and 0 in all other cases. In particular for pure monitoring purposes to discover trends in the gain the simpler algorithm is sufficient. For both algorithms the general procedure is similar: The recipes calculates the gain by first collapsing all input cubes to create a single mean image and variance image. The collapse algorithm specified (clean mean by default) and algorithm parameters are used for this process. Once a mean and variance image has been determined the median of the mean image and the corresponding variance is taken as one data point. The collection of input cubes then lead to a collection of data points of median and variance, giving measurements of the variance vs. median relation for the detector. This is then fitted using a polynomial of the specified order (usually 1 or 2). The slope of this curve is the inverse of the gain while the offset gives an estimate of the read out noise. Note that the read out noise estimate obtained here may not be accurate. Please use the dedicated ron recipe to obtain a more accurate estimate of the RON. The estimates of gain and ron are written as keywords in the main recipe product FITS file. If the vacca parameter is set, the recipe corrects the fitting coefficients for the different noise properties expected for different fowler samples. For example, for double correlated reads this corrects the ron by a factor of 2. If the vacca parameter is not set. The recipe determines non linear pixels in a second step. This is done by performing the gain fitting procedure above for each individual pixel. The resulting map of the gain is the data in the first extension of the main product FITS file. Note that the pixel-by-pixel gain values are often very noisy and can not be used to obtain precise gain measurements. Many exposures per input cube are needed to perform accurate pixel fitting. If the fitorder specified is larger than 1, the second order (quadratic) coefficient of the individual pixel fits is saved in an additional FITS file. All pixels that have second order quadratic coefficient larger than the threshold parameter are flagged as non-linear and this resulting map of flags is written out as a third FITS file.

### 3.3.1.1.6 Products:

| Name                | Type        | Description                                                                                                                                                                                                                                                                                                                                                                                |
|---------------------|-------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IFS_ GAIN           | FITS[Im(4)] | The linear coefficient of the Photon Transfer Curve (PTC) as image. The file contains the gain values in the first extensions. The second extension contains the bad pixels (static input bad pixels), the fourth extension contains the reduced chi-squared values. The third extension is not used and contains a zero image. The header contains the main gain measurement and its rms. |
| IFS_ NONLIN         | FITS[Im(4)] | This product is only created if fitorder > 1. It is identical to the main product except that it contains the second (quadratic) coefficients of the pixel fits in the first extension.                                                                                                                                                                                                    |
| IFS_ NONLIN_ BADPIX | FITS[Im(1)] | A simple image flagging all non linear pixels.                                                                                                                                                                                                                                                                                                                                             |

### 3.3.1.2 sph\_ifs\_master\_dark

#### 3.3.1.2.1 Purpose:

Creation of the master dark frame

#### 3.3.1.2.2 Input frames:

| Data Type (TAG) | Source   | Optional | Min | Max |
|-----------------|----------|----------|-----|-----|
| IFS_ DARK_ RAW  | Raw data | No       | 1   | Any |

#### 3.3.1.2.3 Raw frame keywords used:

none

#### 3.3.1.2.4 Parameters:

| Name                            | Type   | Description                                                                                                                                   | Default                | Allowed vals. |
|---------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------|------------------------|---------------|
| ifs.master_ dark.outfilename    | string | This parameter sets the filename that the product will be written out as. Please also see the esorex documentation about filename of products | master_ dark.fits      | -             |
| ifs.master_ dark.coll_ alg      | int    | Set the collapse algorithm. The vaialable algorithms are: MEAN(0),MEDIAN (1),CLEAN_ MEAN(2). Default is 2 for CLEAN_ MEAN                     | 2                      | 0,1,2         |
| ifs.master_ dark.badpixfilename | string | Controls the filename of the badpixel map.                                                                                                    | static_ badpixels.fits | -             |

| Name                                      | Type   | Description                                                                                                                                                                | Default | Allowed vals. |
|-------------------------------------------|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ifs.master_ dark.clean_ mean.reject_ high | int    | The number of pixels to reject when combining frames at the high end. Number of input frames must be > reject_ high +reject_ low!                                          | 0       | 0-20          |
| ifs.master_ dark.clean_ mean.reject_ low  | int    | The number of pixels to reject when combining frames at the low end. Number of input frames must be > reject_ high +reject_ low!                                           | 0       | 0-20          |
| ifs.master_ dark.sigma_ clip              | double | The sigma clipping value for static badpixel detection.Default is 5.0.                                                                                                     | 5.0     | 0.0-200.0     |
| ifs.master_ dark.smoothing                | double | The smoothing length (FWHM) to use for calculation of the large scale dark structures. Smoothing is needed for good hotpixel detection.                                    | 5.0     | 0.0-200.0     |
| ifs.master_ dark.min_ acceptable          | double | The minimum acceptable value. Any pixels with values below this are marked as bad.                                                                                         | -100.0  | -             |
| ifs.master_ dark.max_ acceptable          | double | The maximum acceptable value. Any pixels with values above this are marked as bad.                                                                                         | 1000.0  | -             |
| ifs.master_ dark.nskip                    | int    | The number of planes in each input raw cube to skip. Removing the first planes in each dark cube in this way removes a spurious ramp effect at the beginning of each dark. | 0       | -             |

#### 3.3.1.2.5 Description:

This recipe deals with the creation of the master dark calibration frame. Only raw frames are used in this recipe. The dark is created by combining the input raw frames using the collapse algorithm specified (usually the clean\_mean algorithm). After all input frames are combined in this way, the badpixels are determined on the result. First a simple thresholding is applied using the parameters min\_accepting and max\_accepting. Now the resulting master dark is smoothed with a gaussian kernel of the FWHM specified in the smoothing user parameter, if this is set to a postive value. This smoothed version is subtracted from the master dark to remove large scale RMS variations. Then sigma clipping is used with the sigma user parameter. All pixels that are further than the specified sigma value away from the mean are marked as bad. The resulting (unsmoothed) master dark frame is written out, including extensions for badpixels, RMS and an extension giving the number of input (raw) pixels for each output pixel. The hotpixel map is also written out as a separate parameter.

#### 3.3.1.2.6 Products:

| Name              | Type        | Description                                                                                                                         |
|-------------------|-------------|-------------------------------------------------------------------------------------------------------------------------------------|
| IFS_ MASTER_ DARK | FITS[Im(4)] | The resulting master dark frame. This frame contains 4 different image extensions: the image, badpixels, the rms and the weightmap. |

| Name                   | Type        | Description                                                                                                                                                |
|------------------------|-------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IFS_STATIC_BADPIXELMAP | FITS[Im(1)] | An optionally written single extension image of the static badpixels. Note that the content is identical to the second extension in the master dark frame. |

### 3.3.1.3 sph\_ifs\_master\_detector\_flat

#### 3.3.1.3.1 Purpose:

Creation of the master detector flat frame

#### 3.3.1.3.2 Input frames:

| Data Type (TAG)             | Source      | Optional | Min | Max |
|-----------------------------|-------------|----------|-----|-----|
| IFS_DETECTOR_FLAT_FIELD_RAW | Raw data    | No       | 2   | 500 |
| IFS_MASTER_DARK             | Calibration | Yes      | 0   | 1   |
| IFS_LARGE_SCALE_FLAT        | Calibration | Yes      | 0   | 1   |
| IFS_PREAMP_FLAT             | Calibration | Yes      | 0   | 1   |
| IFS_STATIC_BADPIXELMAP      | Calibration | Yes      | 0   | 1   |

#### 3.3.1.3.3 Raw frame keywords used:

none

#### 3.3.1.3.4 Parameters:

| Name                                        | Type   | Description                                                                                                                            | Default                   | Allowed vals. |
|---------------------------------------------|--------|----------------------------------------------------------------------------------------------------------------------------------------|---------------------------|---------------|
| ifs.master_detector_flat.outfilename        | string | The output filename for the product. Please also see the esorex documentation for naming of output products.                           | master_detector_flat.fits | -             |
| ifs.master_detector_flat.save_addprod       | bool   | Flag signalling hwether additional products should be saved, in this case a large scale flat, a preamp flat, and a hot pixels product. | 0                         | -             |
| ifs.master_detector_flat.lss_outfilename    | string | The output filename for the large scale flat product. Please also see the esorex documentation for naming of output products.          | large_scale_flat.fits     | -             |
| ifs.master_detector_flat.preamp_outfilename | string | The output filename for the preamplifier flat product. Please also see the esorex documentation for naming of output products.         | preamp_flat.fits          | -             |
| ifs.master_detector_flat.make_badpix        | bool   | Controls if a seperate static badpixel map is requested for output.                                                                    | 0                         | -             |
| ifs.master_detector_flat.badpixfilename     | string | Controls the filename of the badpixel map, if requested for output. Ignored if no make_badpix is FALSE.@pd                             | dff_badpixels.fits        | -             |



| Name                                            | Type   | Description                                                                                                                                                                                                                   | Default | Allowed vals. |
|-------------------------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ifs.master_detector_flat.robust_fit             | bool   | Controls if fitting method is to be a robust linear fit. This will reduce the effect of cosmic rays and other temporary bad pixels. See e.g. Numerical Recipes for a description of the algorithm                             | 0       | -             |
| ifs.master_detector_flat.coll_alg               | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean.                                                                                                                                                          | 2       | 0,1,2         |
| ifs.master_detector_flat.clean_mean.reject_high | int    | The clean mean reject pixels on high end.                                                                                                                                                                                     | 0       | 0-20          |
| ifs.master_detector_flat.clean_mean.reject_low  | int    | The clean mean reject pixels on low end.                                                                                                                                                                                      | 0       | 0-20          |
| ifs.master_detector_flat.badpix_lowtolerance    | double | Threshold value for linearity badpixels. All pixels that have a flat field (slope) below this value will be flagged as bad.                                                                                                   | 0.1     | -             |
| ifs.master_detector_flat.badpix_uptolerance     | double | Threshold value for linearity badpixels. All pixels that have a flat field (slope) above this value will be flagged as bad.                                                                                                   | 10.0    | -             |
| ifs.master_detector_flat.badpix_chisqtolerance  | double | Threshold value for linearity badpixels. All pixels that have chi-squared value for the linear fit that is above this value will be flagged as bad                                                                            | 50.0    | -             |
| ifs.master_detector_flat.lambda                 | double | If this is set to a value $> 0$ , the resulting master flat will be assigned the given calibration wavelength. In case that there are corresponding keywords present in the input raw frames, these are ignored in this case. | -1.0    | -             |
| ifs.master_detector_flat.smoothing_length       | double | The smoothing length for the large scale flats.                                                                                                                                                                               | 10.0    | -             |
| ifs.master_detector_flat.smoothing_method       | int    | The smoothing method to use: 0 is square kernel using cpl_filter, 1 gauss kernel using FFT.                                                                                                                                   | 1       | 0,1           |

### 3.3.1.3.5 Description:

The detector flat field recipe for IFS is very similar to the instrument flat field recipe for IRDIS. The recipe as described here uses input exposures taken with the narrow band or broad band calibration lamps. Several types of flat fields can be produced – in accordance with the calibration plan and the need to have separate flat field components to provide maximal time stability and flat fielding accuracy. The recipe can be used to create a preamplifier correction flat (which can be used to remove the stripe structure caused by the pre amplifiers), a large scale flat field which is a smoothed flat field and hence only shows large scale structures, and a normal flat field. Experience from the SPHERE Data Centre shows that the IFS\_MASTER\_DFF\_LONG files (both at the various wavelengths and the white one) are sufficient to correct the pixel-to-pixel variation in the detector response. The preamplifier correction flat and the large scale flat field (which contains smoothed bad pixels) are not needed for further processing. The recipe creates master calibration frames, using the input exposures which should be taken as described in the IFS calibration plan. The usual procedure to create a flat field is as follows. All raw frames are read in and dark subtracted. The frames are then corrected for the pre-amplifier variations derived from the input

raw data (note that it is currently not possible to skip the pre amplifier correction altogether). This correction is a division operation rather than a subtraction. After this correction, the mean pixel value across the image is determined for all exposures. For every pixel  $p = (x, y)$ , a set of  $m_i, v_i(x, y)$  data pairs are stored with  $m_i$  being the mean value of exposure  $i$  described above, and  $v_i(x, y)$  being the pixel value for pixel  $p(x, y)$  in exposure  $i$ . The flat field value is defined as the slope  $c_i$  of a linear fit  $F$  to the data  $m_i, v_i$ . The resulting slope represents the response of an individual pixel  $p(x, y)$  to illumination relative to the detector mean response. The value will thus naturally be close to 1 and a division by that value will correct for a pixel's deviation from the average detector response. The fit itself is performed either using a maximum likelihood method or a robust fitting method which minimizes the sum of the absolute value of the deviations rather than the sum of the squares of the deviations (see e.g. Numerical Recipes for the algorithm). The robust fitting method will yield better results when significant outliers (e.g. due to cosmic rays) can be expected, but does not allow anything but linear fits and can hence not be used to assess detector non-linearity. The flat field values are saved as an image as the main product of the recipe. Additionally, the recipe may also produce as output a map of all pixels that are identified as non-linear. The criteria for non-linearity are set by the user parameters and can be either pixels that have a flat field value outside specified bounds and/or pixels for which the linear fit produces a reduced chi-squared above a given threshold value. For reliable non-linearity flagging using the reduced chi-squared fit many high quality input exposures are needed. In case that a non zero smoothing value was given, a large scale flat is also created by smoothing the flat field with either a gaussian kernel using FFT or a square kernel using the specific CPL filter algorithm. Unless you know what you are doing leave the default method here which is the FFT smoothing.

### 3.3.1.3.6 Products:

| Name                               | Type        | Description                                                                                                                                                                                                             |
|------------------------------------|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IFS_ MASTER_ DETECTOR_ FLAT_ FIELD | FITS[Im(4)] | The flat field. This is saved as a FITS file with 4 extensions, the flat values, the badpixels (hotpixels and non-linear pixels), the rms error on the flat and a weightmap. Used if the lamp in use cannot be derived. |
| IFS_ MASTER_ DFF_ LONG1            | FITS[Im(4)] | Same as above, produced from all input raw frames which had LAMP1 (1.020mum) switched on                                                                                                                                |
| IFS_ MASTER_ DFF_ LONG2            | FITS[Im(4)] | Same as above, produced from all input raw frames which had LAMP2 (1.230mum) switched on                                                                                                                                |
| IFS_ MASTER_ DFF_ LONG3            | FITS[Im(4)] | Same as above, produced from all input raw frames which had LAMP3 (1.300mum) switched on                                                                                                                                |
| IFS_ MASTER_ DFF_ LONG4            | FITS[Im(4)] | Same as above, produced from all input raw frames which had LAMP4 (1.540mum) switched on                                                                                                                                |
| IFS_ MASTER_ DFF_ LONGBB           | FITS[Im(4)] | Same as above, produced from all input raw frames which had either LAMP5 or LAMP6 (broad band) switched on.                                                                                                             |
| IFS_ PREAMP_ FLAT                  | FITS[Im(4)] | Optional product with a preamp correction flat, formatted as above.                                                                                                                                                     |
| IFS_ LARGE_ SCALE_ FLAT            | FITS[Im(4)] | Optional product with a large scale structure flat, formatted as above.                                                                                                                                                 |

| Name                    | Type        | Description                                                                                                                                                               |
|-------------------------|-------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IFS_NON_LINEAR_PIXELMAP | FITS[Im(1)] | Optional output of all the non-linear pixels determined. All pixels as determined in this recipe using the <code>ird.instrument_flat.badpix_*tolerance</code> parameters. |

### 3.3.1.4 sph\_ifs\_spectra\_positions

#### 3.3.1.4.1 Purpose:

Determinate of the spectra regions on detector

#### 3.3.1.4.2 Input frames:

| Data Type (TAG)           | Source      | Optional | Min | Max |
|---------------------------|-------------|----------|-----|-----|
| IFS_SPECPOS_RAW           | Raw data    | No       | 1   | Any |
| IFS_INSTRUMENT_FLAT_FIELD | Calibration | Yes      | 0   | 1   |
| IFS_CAL_BACKGROUND        | Calibration | Yes      | 0   | 1   |
| IFS_MASTER_DARK           | Calibration | Yes      | 0   | 1   |
| IFS_LENSLET_MODEL         | Calibration | Yes      | 0   | 1   |

#### 3.3.1.4.3 Raw frame keywords used:

none

#### 3.3.1.4.4 Parameters:

| Name                                         | Type   | Description                                                                                                                                                                                                                                                    | Default                | Allowed vals. |
|----------------------------------------------|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|---------------|
| ifs.spectra_positions.outfilename            | string | The output filename for the product. Please also see the esorex documentation for naming of output products.                                                                                                                                                   | spectra_positions.fits | -             |
| ifs.spectra_positions.coll_alg               | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean. A clean mean should be chosen to avoid contamination by cosmic rays.                                                                                                                      | 2                      | 0,1,2         |
| ifs.spectra_positions.clean_mean.reject_high | int    | The clean mean reject pixels on high end. Choose a value above 0 to remove contamination by cosemics.                                                                                                                                                          | 0                      | 0-20          |
| ifs.spectra_positions.clean_mean.reject_low  | int    | The clean mean reject pixels on low end.                                                                                                                                                                                                                       | 0                      | 0-20          |
| ifs.spectra_positions.threshold              | double | The threshold for detection of spectra regions (counts) If this is set to a negative value, the thresholding level is calculated automatically as the sum of the median value of the combined raw frames and the standard deviation on the combined raw frame. | -1.0                   | -             |

| Name                                 | Type   | Description                                                                                                                                                                                                  | Default | Allowed vals. |
|--------------------------------------|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ifs.spectra_positions.minpix         | int    | The minimum number of pixels a connected region has to contain to qualify as a spectra region.                                                                                                               | 25      | -             |
| ifs.spectra_positions.angle          | double | The rotation angle to assume for the lenslet array                                                                                                                                                           | -370.0  | -             |
| ifs.spectra_positions.distortion     | bool   | Flag to set if distortion is to be measured. If set to true, the model is allowed to have distortion, otherwise it is rigid.                                                                                 | 1       | -             |
| ifs.spectra_positions.hmode          | bool   | Flag to set if default model should be Y-JH (TRUE) instead of Y-J (FALSE). Note that this parameter is only effective if no input IFS lenslet model frame is given and the header parameter is set to false. | 0       | -             |
| ifs.spectra_positions.header         | bool   | Flag to set whether to try and set parameters automatically from keywords given in the header of the input files.                                                                                            | 1       | -             |
| ifs.spectra_positions.correct_nonlin | bool   | Apply non-linear correction to wavelength calibration as discovered necessary by D. Mesa in June 2015                                                                                                        | 1       | -             |

#### 3.3.1.4.5 Description:

This recipe associates the IFS spectra with lenslets and associates pixels with wavelengths. The wavelengths are an initial estimation from the lenslet model and the sph\_ifs\_wave\_calib should be used to refine them. The raw frames are reduced by optionally dark subtracting either a master background or a master dark and by flat fielding and then combined using the combination algorithm chosen (usually the clean mean algorithm). The flat field used can be either a detector flat field, a flat field of the whole instrument (detector+IFU) or any other flat deemed to be useful for this purpose. In most cases a detector flat field obtained with the broad band calibration lamp seems the best choice. After a combined and reduced frame has been produced the following algorithm is applied:

- A thresholding algorithm will determine the spectra regions from the combined frame. From the regions a point pattern is calculated. A point pattern is a list of points. In this case the points are the centers of the regions;
- Calculate the average width of the spectra regions and use it to scale the width and the stretch factors (x and y directions) of the IFS lenslet model;
- A second point pattern is then determined using the (scaled) IFS lenslet model. If a IFS lenslet model was provided in the form of a FITS file with the model parameters as keywords in its header, this model is used, otherwise the default model is used, please see the description of the lenslet model in the section on static calibrations;
- The expected point pattern is compared with the actual one to determine a relative scale and an offset;
- The IFS lenslet model used for the expected pattern is subsequently scaled and shifted accordingly to reflect the new, actual values of scale and position.
- If desired, the distortion is calculated. This may be crucial to ensure correct wavelength calibrations later in the calibration cascade. If distortion is allowed (using the



ifs.spectra\_positions.distortion parameter) then the recipe will also fit a 2D polynomial of 4th order in x and y directions to the difference between measured and predicted point patterns. The coefficients of this polynomial model are incorporated in the IFS\_SPECPOS product and will be used subsequently in all recipes making use of the created lenslet model file.

- For each pixel having coordinates  $(x, y)$  an initial wavelength estimation is calculated. For each point the polygon it belongs to is calculated according to the refined model. The polygon can be rotated, therefore a new aligned polygon having the same center, width and height is calculated. The lower  $y$  coordinate  $y_{low}$  of the aligned polygon is used to calculate the corresponding wavelength  $\lambda(y)$ :

$$\lambda(y) = (y - 0.5 - y_{low}) \cdot d + \lambda_{min} \quad (3.3)$$

where  $d$  is the model dispersion and  $\lambda_{min}$  is the minimum wavelength according to the model;

- A non linear correction is then applied to  $\lambda(y)$  if ifs.spectra\_positions.correct\_nonlin = TRUE:

$$\lambda'(y) = a \cdot \lambda^2(y) + (b + 1) \cdot \lambda(y) + c \quad (3.4)$$

where  $a$ ,  $b$  and  $c$  are 0.30870, -0.74312, 0.41505 in H mode and 0.67754, -1.4464, 0.75754 in Y mode respectively;

Finally the calculated data (mode, wavelengths, distortion) is used to construct a pixel description table which is saved, together with the corrected lenslet model parameters, as the primary product of this recipe.

#### 3.3.1.4.6 Products:

| Name        | Type        | Description                                                                                                                                                                                                                                                                                                                   |
|-------------|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IFS_SPECPOS | FITS[Im(6)] | The resulting pixel description table (PDT) written out as images. The PDT is written as a FITS file with 6 extensions, corresponding to: wavelength, spectra region id, lenslet id, wavelength width, second derivate of wavelength and illumination fraction. Currently the last two extensions are not used in any recipe. |

#### 3.3.1.5 sph\_ifs\_instrument\_flat

##### 3.3.1.5.1 Purpose:

Determine the full instrument flat field OR the IFU flat

### 3.3.1.5.2 Input frames:

| Data Type (TAG)       | Source      | Optional | Min | Max |
|-----------------------|-------------|----------|-----|-----|
| IFS_FLAT_FIELD_RAW    | Raw data    | No       | 1   | Any |
| IFS_WAVECALIB         | Calibration | Yes      | 0   | 1   |
| IFS_SPECPOS           | Calibration | Yes      | 0   | 1   |
| IFS_CAL_BACKGROUND    | Calibration | Yes      | 0   | 1   |
| IFS_MASTER_DARK       | Calibration | Yes      | 0   | 1   |
| IFS_MASTER_DFF_LONG1  | Calibration | No       | 1   | 1   |
| IFS_MASTER_DFF_LONG2  | Calibration | No       | 1   | 1   |
| IFS_MASTER_DFF_LONG3  | Calibration | No       | 1   | 1   |
| IFS_MASTER_DFF_LONG4  | Calibration | Yes      | 0   | 1   |
| IFS_MASTER_DFF_LONGBB | Calibration | Yes      | 0   | 1   |
| IFS_PREAMP_FLAT       | Calibration | Yes      | 0   | 1   |
| IFS_MASTER_DFF_SHORT  | Calibration | Yes      | 0   | 1   |

### 3.3.1.5.3 Raw frame keywords used:

none

### 3.3.1.5.4 Parameters:

| Name                                       | Type   | Description                                                                                                                                                                                       | Default                  | Allowed vals. |
|--------------------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|---------------|
| ifs.instrument_flat.iff_filename           | string | The output filename for the instrument flat product. Please also see the esorex documentation for naming of output products.                                                                      | ifs_instrument_flat.fits | -             |
| ifs.instrument_flat.ifu_filename           | string | The output filename for the IFU flat product. Please also see the esorex documentation for naming of output products.                                                                             | ifs_ifu_flat.fits        | -             |
| ifs.instrument_flat.make_badpix            | bool   | Controls if a sepearte static badpixel map is requested for output.                                                                                                                               | 0                        | -             |
| ifs.instrument_flat.nofit                  | bool   | Allows polynomial fitting for flat field determination to be turned off. Instead the input raw frames will simply be collapsed with a median.                                                     | 0                        | -             |
| ifs.instrument_flat.robust_fit             | bool   | Controls if fitting method is to be a robust linear fit. This will reduce the effect of cosmic rays and other temporary bad pixels. See e.g. Numerical Recipes for a description of the algorithm | 0                        | -             |
| ifs.instrument_flat.badpixfilename         | string | Controls the filename of the badpixel map, if requested for output. Ignored if no make_badpix is FALSE.                                                                                           | iff_badpixels.fits       | -             |
| ifs.instrument_flat.coll_alg               | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = clean mean, 3 = Weighted mean.                                                                                                           | 1                        | 0,1,2         |
| ifs.instrument_flat.clean_mean.reject_high | int    | The clean mean reject pixels on high end.                                                                                                                                                         | 0                        | 0-20          |

| Name                                              | Type   | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Default | Allowed vals. |
|---------------------------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ifs.instrument_<br>flat.clean_<br>mean.reject_low | int    | The clean mean reject pixels on low end.                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0       | 0-20          |
| ifs.instrument_<br>flat.badpix_<br>lowtolerance   | double | Threshold value for linearity badpixels. All pixels that have a flat field (slope) below this value will be flagged as bad                                                                                                                                                                                                                                                                                                                                                                  | 0.1     | -             |
| ifs.instrument_<br>flat.badpix_<br>uptolerance    | double | Threshold value for linearity badpixels. All pixels that have a flat field (slope) above this value will be flagged as bad                                                                                                                                                                                                                                                                                                                                                                  | 10.0    | -             |
| ifs.instrument_<br>flat.badpix_<br>chisqtolerance | double | Threshold value for linearity badpixels. All pixels that have chi-squared value for the linear fit that is above this value will be flagged as bad                                                                                                                                                                                                                                                                                                                                          | 50.0    | -             |
| ifs.instrument_<br>flat.use_illumination          | bool   | Controls if the illumination pattern of lenslets is to be taken into account in the cube creation or not. A low level wave-like structure can appear in the result if it is not applied. However, calculation of the illumination fraction affects the performance of the recipe and so this option should only be enabled if the artefacts adversely affect the results. Note that there is a corresponding option on the ifs_science_dr recipe which should match the chosen option here. | 0       | -             |

### 3.3.1.5.5 Description:

This recipe creates the instrument flat for IFS. The recipe works in two modes: in the first mode, the raw frames from the calibration procedure are used to create a flat field on the detector which includes the effect of the detector response (the detector flat field is NOT divided out). The product created in this mode may be used as a flat field in the spectra\_positions or wave\_calib recipe. In the second mode, the pixel description table produced by the spectra\_positions recipe and updated by wavelength calibration recipe is used as input together with the calibration raw frames to create a flat field of the IFU which has the effect of the detector response removed (i.e. it is divided by the detector flat). The mode to use is decided depending on the parameters set for this recipe and the input files available. In the total flat field mode the recipe reads in the spectra positions file to set the illuminated regions. The recipe then constructs a flat field in the same way as done for sph\_ifs\_master\_detector\_flat (optionally first subtracting either a master background or a master dark). The resulting frames is then saved as the total instrument flat. Note that this frame has the same dimensions as the detector and is always dithering dependent. In the IFU flat field mode, the wavelength calibration file is used instead of the spectra positions table. First the same steps are carried out as for the total flat mode. However, the wavelength calibration file is then used to first construct a wavelength dependent flat field (also sometimes called a super flat field), making use of the series of master detector flats provided. This frame is then used to flat field the combined raw frames by dividing it out, to give a flat field containing only the IFU (lenslet) contribution. At this stage the frame is still for the detector itself. A lenslet description table is then constructed using the lenslet model as obtained from the header of the input wavelength calibration frame. This lenslet description table now contains the extracted spectra data for all lenslets. These are then collapsed along the wavelength direction (taking the median values) to obtain a flat field value for all lenslets. The primary data product is written

out as a viewable interpolated image (which is not generally used further in the cascade) and a table containing the flat field values for all lenslets. This table is used in other recipes when the IFU flat field is to be applied.

### 3.3.1.5.6 Products:

| Name                         | Type            | Description                                                                                                                                                                                                                                  |
|------------------------------|-----------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IFS_ INSTRUMENT_ FLAT_ FIELD | FITS[Im(4)]     | The total instrument flat field. This is saved as a FITS file with 4 extensions, the flat values, the badpixels (hotpixels and non-linear pixels), the rms error on the flat and a weightmap.                                                |
| IFS_ IFU_ FLAT_ FIELD        | FITS[Im(4),Tab] | The IFU flat field. This is saved as a FITS file with 4 image extensions, the flat values, the badpixels (hotpixels and non-linear pixels), the rms error on the flat, a weightmap and 1 table extension containing the lenslet flat values. |
| IFS_ STATIC_ BADPIXELMAP     | FITS[Im(1)]     | Optional output of all the non-linear pixels determined. All pixels as determined in this recipe using the <code>ird.instrument_flat.badpix_*tolerance</code> parameters.                                                                    |

### 3.3.1.6 sph\_ifs\_wave\_calib

#### 3.3.1.6.1 Purpose:

Create the wavelength calibration data

#### 3.3.1.6.2 Input frames:

| Data Type (TAG)              | Source      | Optional | Min | Max |
|------------------------------|-------------|----------|-----|-----|
| IFS_ WAVECALIB_ RAW          | Raw data    | No       | 1   | Any |
| IFS_ SPECPOS                 | Calibration | No       | 1   | 1   |
| IFS_ INSTRUMENT_ FLAT_ FIELD | Calibration | Yes      | 0   | 1   |
| IFS_ CAL_ BACKGROUND         | Calibration | Yes      | 0   | 1   |
| IFS_ MASTER_ DARK            | Calibration | Yes      | 0   | 1   |

#### 3.3.1.6.3 Raw frame keywords used:

none

#### 3.3.1.6.4 Parameters:

| Name                       | Type   | Description                                                    | Default             | Allowed vals. |
|----------------------------|--------|----------------------------------------------------------------|---------------------|---------------|
| ifs.wave_calib.outfilename | string | The output filename of the calibrated IFS model.               | pdt_wave_calib.fits | -             |
| ifs.wave_calib.coll_alg    | int    | The collapse algorithm to use to combine the input raw frames. | 2                   | 0,1,2         |

| Name                                  | Type   | Description                                                                                                                                                                                                                               | Default | Allowed vals. |
|---------------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ifs.wave_<br>calib.number_lines       | int    | The number of wavelength lines to fit.<br>A number of zero (default) means automatic setting. In that case the number of wavelengths and the wavelengths themselves are set automatically from the header of the pixel description table. | 0       | 0-5           |
| ifs.wave_<br>calib.wavelength_line1   | double | The wavelength of the first line                                                                                                                                                                                                          | 0.98772 | 0.9-2.5       |
| ifs.wave_<br>calib.wavelength_line2   | double | The wavelength of the second line                                                                                                                                                                                                         | 1.12371 | 0.9-2.5       |
| ifs.wave_<br>calib.wavelength_line3   | double | The wavelength of the third line (only used if number_lines > 2)                                                                                                                                                                          | 1.30937 | 0.9-2.5       |
| ifs.wave_<br>calib.wavelength_line4   | double | The wavelength of the fourth line (only used if number_lines > 3)                                                                                                                                                                         | 1.5451  | 0.9-2.5       |
| ifs.wave_<br>calib.wavelength_line5   | double | The wavelength of the fourth line (only used if number_lines > 4)                                                                                                                                                                         | 1.5451  | 0.9-2.5       |
| ifs.wave_calib.line_threshold         | double | The threshold value to use for identifying spectral lines.                                                                                                                                                                                | 90.0    | 0.0-40000.0   |
| ifs.wave_calib.polyfit_order          | int    | The order of the polynomial to use for the wavelength model. For example, if the order is 1, a linear model with constant dispersion is assumed.                                                                                          | 2       | -             |
| ifs.wave_calib.no_spline_interpol     | bool   | Do not use esoteric spline interpolation after wavelength fit. If true, the polynomial fit result will be directly inserted into the spectra without endpoint adaptation.                                                                 | 1       | -             |
| ifs.wave_calib.fit_window_size        | int    | Half the tolerance around the predicted wavelength position to search for the actual maximum. This value should absolutely be smaller than the minimal distance between line wavelengths (in pixels).                                     | 4       | 1-10          |
| ifs.wave_calib.clean_mean.reject_high | int    | Number of pixels to reject at high end for the clean mean combination method.                                                                                                                                                             | 0       | 0-20          |
| ifs.wave_calib.clean_mean.reject_low  | int    | Number of pixels to reject at low end for the clean mean combination method.                                                                                                                                                              | 0       | 0-20          |
| ifs.wave_calib.save_addprod           | bool   | Flag to signal whether additional products - in this case the wavelength calibrated cube - should be saved.                                                                                                                               | 0       | -             |

### 3.3.1.6.5 Description:

This is the recipe responsible for calibrating the pixel to wavelength associations for the IFS. The approach taken for the IFS in SPHERE is model based: the initial model as created by the spectra positions calibration recipe is used as input and the observed wavelength calibration frames are used to modify this model, adjusting the pixel to wavelength associations. This approach assumes implicitly that there are no large discrepancies between the model and the actual wavelength associations. Before the wavelength associations are determined, the raw input frames are combined using the specified combination method (mean, clean mean or median). Optionally either a master background or a master dark dark is subtracted and the result is divided by an



optional flat field. The recipe then extracts a one dimensional spectrum for each spectral region (as found in the spectra positions recipe). The  $i$ -th spectrum has wavelengths  $w^{(i)}(y)$  and flux  $s^{(i)}(y)$  where  $y$  is the pixel index in the wavelength direction. Around each of the line  $l$  with wavelength  $w_l$  as specified in the user input, the flux weighted mean position is determined in a window around the expected position with a width as specified by the `fit_window_size` parameter:

$$y'_l = \frac{\sum_{y=y_{min}}^{y_{max}} s(y)^2 \cdot y}{\sum_{y=y_{min}}^{y_{max}} s(y)^2} \quad (3.5)$$

where  $y_{min} = y(w_l) - \Delta w$  if this is positive and  $y_{min} = 0$  otherwise, and  $y_{max} = y(w_l) + \Delta w$  if this is smaller than the total spectra length in pixels  $N$  and  $y_{max} = N$  otherwise. The window region should be chosen so as to avoid cases where there is none or more than one sharp line within the region of width  $2\Delta w$  around the predicted pixel for the wavelength  $w_l$ . Once parameters  $y'_l$  have been determined for all  $l = 1..n_l$  for a spectrum, a polynomial fit is performed to the  $y'_l$  vs.  $w_l$  data. This polynomial is then used to fill in the wavelength associations for all pixels in the region of that spectrum. More specifically, for the  $i$ -th spectrum a vector of wavelengths  $w_c^{(i)}(y)$  is generated associating the  $y$ -th pixel with the corresponding wavelength. In cases when no fitting was possible (for example due to the fact that not enough identifiable lines were present in the spectra region) or if the resulting wavelength associations for the minimum and maximum wavelengths of the spectrum is different by more than 3 times the dispersion to the expected value, the assigned wavelengths of the model are used (even if a new association was found). In case no spectrum could be extracted in the first place, all wavelengths are set to zero and all pixels in the spectra region thereby marked as bad. Hence, ignoring the spectra marked as bad regions, for the  $i$ -th spectrum the final wavelengths vector  $w_f^{(i)}$  is:

$$w_f^{(i)} = \begin{cases} w^{(i)} & \text{if } w_c^{(i)} \text{ deviates too much from } w^{(i)} \\ w_c^{(i)} & \text{otherwise} \end{cases} \quad (3.6)$$

And for every  $i$ -th spectrum the following QC values are calculated:

- $w_{min}^{(i)} = \min w_f^{(i)}$
- $w_{MAX}^{(i)} = \max w_f^{(i)}$
- $w_{cent}^{(i)} = w_f^{(i)}(\frac{N-1}{2})$

Finally the resolving power  $r_p^{(i)}(y)$  of the  $i$ -th spectrum is calculated as follows:

$$r_p^{(i)}(y) = \frac{w_f^{(i)}(y) + w_f^{(i)}(y+1)}{2(w_f^{(i)}(y+1) - w_f^{(i)}(y))} \quad (3.7)$$

lastly the median resolving power for the  $i$ -th spectrum is:

$$r(i) = \text{median}(r_p^{(i)}) \quad (3.8)$$

When all spectra have been processed in this way, the final, now corrected, pixel description table is written out as the main recipe product. Several quality control keywords are provided in the header to help monitor the quality of the calibration. In particular:

- “ESO QC MEDIAN DISPERSION” =  $d_m = \text{median}(d)$ , where  $d$  is the dispersion image related to the output pixel description table;
- “ESO QC MEDIAN RESOLVING POWER” =  $\text{median}(r(i))$ .

- “ESO DRS MEDIAN MIN WAVEL” =  $\text{median}(w_{min}(i)) - \frac{d_m}{2}$
- “ESO DRS MEDIAN MAX WAVEL” =  $\text{median}(w_{MAX}(i)) + \frac{d_m}{2}$ ;
- “ESO DRS MEDIAN CENT WAVEL” =  $\text{median}(w_{cent}(i))$ .

As of SPHERE 0.42.0b, an additional resolving power calculation is performed as follows:

- A median collapse spectrum is formed from the `IFS_WAVECALIB_CUBE` product by computing the median of the good pixels in each plane of the cube (excluding the 60 pixels closest to each image edge);
- A Gaussian fit is made to each of the laser lamp arc lines in the median collapse spectrum (3 lines in YJ, 4 in YJH). The fit is made in flux as a function of pixel coordinate along the spectrum;
- A linear fit is then made between the known wavelengths of the laser lamp arc lines as a function of the fitted pixel coordinate of those lines.

From these calculations, the following header keywords are populated and saved in both the `IFS_WAVECALIB` and `IFS_WAVECALIB_CUBE` products:

- The integrated flux of laser line n is stored as `ESO QC FLUX LASERn`;
- The resolving power of laser line n (i.e.,  $\lambda_0/\Delta_\lambda$ , where  $\lambda_0$  is the nominal wavelength of the laser lamp and  $\Delta_\lambda$  is the FWHM of the Gaussian fit) is stored as `ESO QC RESPOW LASERn`;
- The wavelength-to-pixel scale, i.e. the gradient of the linear fit described above, is stored as `ESO QC DISPERSION`;
- The RMS value of the linear fit described above (formally, the coefficient of determination, commonly referred to as  $R^2$ ), is stored as `ESO QC DISPERSION RMS`.
- The wavelength in pixel 1 (i.e. the first pixel), as determined by the linear fit described above, is stored as `ESO QC MIN LAMBDA`.

### 3.3.1.6.6 Products:

| Name                 | Type            | Description                                                                                                                                                                                                                                                                                                                                                                                            |
|----------------------|-----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IFS_ WAVECALIB       | FITS[Im(7)]     | The calibrated pixel description table (PDT) written out as images. The PDT is written as a FITS file with 6 extensions, corresponding to: wavelength, spectra region id, lenslet id, wavelength width, second derivate of wavelength and illumination fraction. The last extension flags bad spectra for which no good fit was found. Currently the last three extensions are not used in any recipe. |
| IFS_ WAVECALIB_ CUBE | FITS[Imcube(4)] | The wavelength calibrated cube.                                                                                                                                                                                                                                                                                                                                                                        |

### 3.3.1.7 sph\_ifs\_star\_center

#### 3.3.1.7.1 Purpose:

Determine the field centre

#### 3.3.1.7.2 Input frames:

| Data Type (TAG)            | Source      | Optional | Min | Max |
|----------------------------|-------------|----------|-----|-----|
| IFS_STAR_CENTER_WAFFLE_RAW | Raw data    | No       | 1   | Any |
| IFS_MASTER_DFF_LONG1       | Calibration | Yes      | 0   | 1   |
| IFS_MASTER_DFF_LONG2       | Calibration | Yes      | 0   | 1   |
| IFS_MASTER_DFF_LONG3       | Calibration | Yes      | 0   | 1   |
| IFS_MASTER_DFF_LONG4       | Calibration | Yes      | 0   | 1   |
| IFS_MASTER_DFF_LONGBB      | Calibration | Yes      | 0   | 1   |
| IFS_PREAMP_FLAT            | Calibration | Yes      | 0   | 1   |
| IFS_MASTER_DFF_SHORT       | Calibration | Yes      | 0   | 1   |
| IFS_IFU_FLAT_FIELD         | Calibration | Yes      | 0   | 1   |
| IFS_MASTER_DARK            | Calibration | Yes      | 0   | 1   |
| IFS_STATIC_BADPIXELMAP     | Calibration | Yes      | 0   | 1   |
| IFS_WAVECALIB              | Calibration | No       | 1   | 1   |
| IFS_DISTORTION_MAP         | Calibration | Yes      | 0   | 1   |

#### 3.3.1.7.3 Raw frame keywords used:

none

#### 3.3.1.7.4 Parameters:

| Name                                   | Type   | Description                                                                                                               | Default          | Allowed vals. |
|----------------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------|------------------|---------------|
| ifs.star_center.outfilename            | string | The output filename for the product.<br>Please also see the esorex documentation for naming of output products.           | star_center.fits | -             |
| ifs.star_center.coll_alg               | int    | The collapse algorithm to use. 0 = Mean, 1 = Median.                                                                      | 1                | 0,1           |
| ifs.star_center.clean_mean.reject_high | int    | The clean mean reject pixels on high end.                                                                                 | 1                | 0-20          |
| ifs.star_center.clean_mean.reject_low  | int    | The clean mean reject pixels on low end.                                                                                  | 1                | 0-20          |
| ifs.star_center.sigma                  | double | The sigma threshold to use for source detection                                                                           | 10.0             | -             |
| ifs.star_center.use_waffle             | bool   | Flag to whether to expect a waffle image (4 images in cross formation) or not (single central fit).                       | 1                | -             |
| ifs.star_center.qc                     | bool   | If set QC output for this recipe is produced.                                                                             | 0                | -             |
| ifs.star_center.save_interprod         | bool   | Flag to signal if intermediate products should be kept                                                                    | 0                | -             |
| ifs.star_center.unsharp_window         | int    | Before finding centres an unsharp algorithm is used on the image. This specifies the window width for the mask in pixels. | 4                | -             |

| Name                        | Type | Description                                               | Default | Allowed vals. |
|-----------------------------|------|-----------------------------------------------------------|---------|---------------|
| ifs.star_center.qc_window_x | int  | This specifies the window width for QC output in pixels.  | 256     | -             |
| ifs.star_center.qc_window_y | int  | This specifies the window height for QC output in pixels. | 256     | -             |

#### 3.3.1.7.5 Description:

This recipe creates a table with centre star positions. The input raw frames are each reduced by subtracting the dark and applying the flat provided. After sorting the frames, the recipe only reduces the image data of the waffle images. An optional mask frame may be given, of the same dimensions as the raw input frames, which allows masking out of regions before the point sources are detected. This can mainly be used on images where despite use of a coronagraph a significant central signal is present. The left and right parts of the illuminated detector regions are extracted and left and right part are seperately analysed using a aperture detection algorithm. The aperture detection algorithm detects all connected regions of at least 4 pixels size (area) that are the given sigma above the background. The so detected waffle stars are then used to contruct a geometric centre of all stars found. This is then the frame centre. The recipe also works for the case that there is only one star (e.g. the coronagraph is out and no waffle stars are formed). After frame centers have been determined for all waffle images an internal table is created with an entry for each waffle image, giving the time of the start of the exposure and the centre information. The recipe reads the position of the IFS DMS from the header of the raw frames, divides by 18.0 to convert from micron to pixels, and stores them in the output table.

#### 3.3.1.7.6 Known Issues:

While this recipe is functional, its requirements are fully settled. The recipeimplements the current baseline of how star centering is foreseen in IFS.

#### 3.3.1.7.7 Products:

| Name            | Type        | Description                                                                                                                                           |
|-----------------|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| IFS_STAR_CENTER | FITS[Table] | The table of stellar center positions as a FITS table, with one row for each input raw frame. The order is the same as the order of input raw frames. |

### 3.3.1.8 sph\_ifs\_science\_dr

#### 3.3.1.8.1 Purpose:

Reduce science observations

### 3.3.1.8.2 Input frames:

| Data Type (TAG)          | Source      | Optional | Min | Max |
|--------------------------|-------------|----------|-----|-----|
| IFS_ SCIENCE_ DR_ RAW    | Raw data    | No       | 1   | 500 |
| IFS_ MASTER_ DFF_ LONG1  | Calibration | Yes      | 0   | 1   |
| IFS_ MASTER_ DFF_ LONG2  | Calibration | Yes      | 0   | 1   |
| IFS_ MASTER_ DFF_ LONG3  | Calibration | Yes      | 0   | 1   |
| IFS_ MASTER_ DFF_ LONG4  | Calibration | Yes      | 0   | 1   |
| IFS_ MASTER_ DFF_ LONGBB | Calibration | Yes      | 0   | 1   |
| IFS_ PREAMP_ FLAT        | Calibration | Yes      | 0   | 1   |
| IFS_ MASTER_ DFF_ SHORT  | Calibration | Yes      | 0   | 1   |
| IFS_ IFU_ FLAT_ FIELD    | Calibration | Yes      | 0   | 1   |
| IFS_ CAL_ BACKGROUND     | Calibration | Yes      | 0   | 1   |
| IFS_ MASTER_ DARK        | Calibration | Yes      | 0   | 1   |
| IFS_ STATIC_ BADPIXELMAP | Calibration | Yes      | 0   | 1   |
| IFS_ WAVECALIB           | Calibration | No       | 1   | 1   |
| IFS_ DISTORTION_ MAP     | Calibration | Yes      | 0   | 1   |

### 3.3.1.8.3 Raw frame keywords used:

| Keyword            | Type   | Optional | Description                                          |
|--------------------|--------|----------|------------------------------------------------------|
| ESO INS2 DITH POSX | double | Yes      | The dithering position in X for the frame in pixels. |
| ESO INS2 DITH POSY | double | Yes      | The dithering position in Y for the frame in pixels. |

### 3.3.1.8.4 Parameters:

| Name                                        | Type   | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Default               | Allowed vals. |
|---------------------------------------------|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|---------------|
| ifs.science_<br>dr.outfilename              | string | The output filename for the product.<br>Please also see the esorex documentation for naming of output products.                                                                                                                                                                                                                                                                                                                                                                                    | ifs_ science_ dr.fits | -             |
| ifs.science_ dr.coll_ alg                   | int    | The collapse algorithm to use when creating a product with ADI. 0 = Mean, 1 = Median, 3 = Weighted mean.                                                                                                                                                                                                                                                                                                                                                                                           | 3                     | 0,1,3         |
| ifs.science_ dr.clean_<br>mean.reject_ high | int    | The clean mean reject pixels on high end. Not currently used.                                                                                                                                                                                                                                                                                                                                                                                                                                      | 0                     | 0-20          |
| ifs.science_ dr.clean_<br>mean.reject_ low  | int    | The clean mean reject pixels on low end. Not currently used.                                                                                                                                                                                                                                                                                                                                                                                                                                       | 0                     | 0-20          |
| ifs.science_ dr.use_<br>illumination        | bool   | Controls if the illumination pattern of lenslets is to be taken into account in the cube creation or not. A low level wave-like structure can appear in the result if it is not applied. However, calculation of the illumination fraction affects the performance of the recipe and so this option should only be enabled if the artefacts adversely affect the results. Note that there is a corresponding option on the ifs_ instrument_ flat recipe which should match the chosen option here. | 0                     | -             |



| Name                                | Type   | Description                                                                                                                                                                                                                                                                                                                                                                       | Default         | Allowed vals. |
|-------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|---------------|
| ifs.science_dr.use_adi              | int    | Use of ADI. If set to 0 angular differential imaging is not applied. If set to 1 then ADI is always applied if it is set to 2 then ADI is applied only if the total rotation in the input frames is larger than the angle given in the ifs.science_dr.min_adi_angle parameter. Note that the parameters to the ADI algorithm are fixed - it uses an FFT transform with no filter. | 2               | 0,1,2         |
| ifs.science_dr.min_adi_angle        | double | Minimum angle for automatic ADI switch. When use_adi is set to automatic then the ADI is used iff the total rotation angle covered over the whole input is larger than the given value.                                                                                                                                                                                           | 4.0             | -             |
| ifs.science_dr.spec_deconv          | bool   | If set to true, spectra deconvolution is used to combine the cubes.                                                                                                                                                                                                                                                                                                               | 1               | -             |
| ifs.science_dr.spec_deconv_filename | string | The basename for the spectra deconvolution output files (without the .fits extension). Files will be named using a running number.                                                                                                                                                                                                                                                | ifs_spec_deconv | -             |
| ifs.science_dr.order                | int    | The order of the polynomial fit to be subtracted. [Currently fixed at 5 when ifs.science_dr.spec_deconv = TRUE]                                                                                                                                                                                                                                                                   | 2               | 1-10          |
| ifs.science_dr.user_cent            | bool   | If set to true, the user supplied center values are used, overriding the internally derived centers. [Currently fixed at FALSE when ifs.science_dr.spec_deconv = TRUE]                                                                                                                                                                                                            | 0               | -             |
| ifs.science_dr.cx                   | double | If user_cent set to TRUE, this is the centre x coordinate to use. Coordinates are in FITS coords, so that the centre of a 291 times 291 pixel image is at 146.0,146.0. Unused if ifs.science_dr.spec_deconv = TRUE as user_cent is then fixed to FALSE.                                                                                                                           | 146.0           | -             |
| ifs.science_dr.cy                   | double | If user_cent set to TRUE, this is the centre y coordinate to use. Coordinates are in FITS coords, so that the centre of a 291 times 291 pixel image is at 146.0,146.0. Unused if ifs.science_dr.spec_deconv = TRUE as user_cent is then fixed to FALSE.                                                                                                                           | 146.0           | -             |



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| Name                                        | Type   | Description                                                                                                                                                                                                                                                                                                                       | Default    | Allowed vals. |
|---------------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|---------------|
| ifs.science_<br>dr.reflambda                | double | The reference wavelength to use. Be careful with this parameter since the quality of the FFT scaling depends on this parameter. Scaling quality is generally better when choosing a value for the reference wavelength at the higher end of the spectra range.<br>[Currently fixed at 1.0 when ifs.science_dr.spec_deconv = TRUE] | 1.3        | -             |
| ifs.science_dr.fwhm                         | double | A smoothing FWHM that will be used to improve the cosmetics. Smoothing is disabled if the parameter is 0 or negative. [Currently fixed at 2.0 when ifs.science_dr.spec_deconv = TRUE]                                                                                                                                             | -1.0       | -             |
| ifs.science_<br>dr.badpixco.apply           | bool   | Flag to set the application of the automatic badpixel correction                                                                                                                                                                                                                                                                  | 0          | -             |
| ifs.science_<br>dr.xtalkco.apply            | bool   | Flag to set the application of the cross talk correction                                                                                                                                                                                                                                                                          | 0          | -             |
| ifs.science_<br>dr.xtalkco.largescale.apply | bool   | Flag to set the application of the large scale crosstalk correction. If set to false, only the small-scalecrosstalk gets corrected which usually yields better results.                                                                                                                                                           | 0          | -             |
| ifs.science_<br>dr.xtalkco.sepmax           | int    | The sliding correction window half-size (the window size is $2 * \text{sepmax} + 1$ )                                                                                                                                                                                                                                             | 20         | -             |
| ifs.science_<br>dr.xtalkco.bfac             | double | The parameter bfactor in the small talk cross talk correction. To correct values, the central subwindow pixel value times $1.0/(1.0 + \text{pow}(\text{rdist}/\text{bfac}, \text{powfac}))$ is subtracted, with rdist the pixel distance to the central subwindow pixel.                                                          | 0.40443667 | -             |
| ifs.science_<br>dr.xtalkco.powfac           | double | The parameter powfac in the small talk cross talk correction. To correct values, the central subwindow pixel value times $1.0/(1.0 + \text{pow}(\text{rdist}/\text{bfac}, \text{powfac}))$ is subtracted, with rdist the pixel distance to the central subwindow pixel.                                                           | 3.0        | -             |
| ifs.science_<br>dr.xtalkco.lgscalewin       | int    | The large scale cross talk correction subwindow size.                                                                                                                                                                                                                                                                             | 64         | -             |
| ifs.science_<br>dr.xtalkco.threshold        | double | The large scale crosstalk correction threshold to use. Any values that are in between -threshold and +threshold will be set to the median image value.                                                                                                                                                                            | 50000.0    | -             |
| ifs.science_<br>dr.xtalkco.smoothing        | double | The large scale crosstalk correction threshold smoothing fwhm to use, This is used to to smooth the image before subtracting from the original.                                                                                                                                                                                   | 100.0      | -             |

| Name                                  | Type   | Description                                                                                                                                                                                                                                                                                | Default | Allowed vals. |
|---------------------------------------|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ifs.science_<br>dr.xtalkco.stephist   | double | The bin size to use for the creation of the pixel histogram for the most likely value find. The most likely value is found in each subwindow and the smmothed version of these subtracted from the original.                                                                               | 20.0    | -             |
| ifs.science_<br>dr.badpixco.threshold | double | The absolute threshold for badpixel correction to use. This is applied in a logical AND operation with the badpixel correction factor threshold. Any pixels above this value, that are also above badpixco.fac * median, are set to the median of the surrounding 8 pixels.                | 100.0   | -             |
| ifs.science_<br>dr.badpixco.fac       | double | The absolute threshold factor for badpixel correction to use. This is applied in a logical AND operation with the absolute badpixel correction threshold. Any pixels above badpixco.fac * median AND also above the absolute threshold, are set to the median of the surrounding 8 pixels. | 5.0     | -             |
| ifs.science_<br>dr.badpixco.border    | int    | The border size in pixel to ignore for the purpose of badpixel correction.                                                                                                                                                                                                                 | 100     | -             |

#### 3.3.1.8.5 Description:

This is the science calibration recipe for IFS. The input raw observation frames are reduced by dark subtracting each one, if a master background or alternatively a master dark frame is given as input. Also, in case a pre-amplifier correction frame (basically for de-stripping) the raw frames are corrected for the stripes. The large scale effects are then corrected by creating a so called super flat that combines the (large scale) flat fields taken with different colour lamps into a single flat field that takes the pixel to wavelength correspondence into account using the information from the input wavelength calibration file. After dividing out the super flat, a broad band flat field that should have been created from recent data is divided out to remove the (small scale) flat variations that are very time dependent. Note that this broad band master flat field should already be corrected for the large scale flat structure. This means it must have been created using the master flat field recipe with a large scale flat as input. The recipe allows automatic combination of images using the spec\_deconv and simple\_adi routines. These reduction steps can be selective switched on or off. To combine frames manually, the recipe the use\_adi and spec\_deconv flags should be set to false. Note that the ADI and spectral deconvolution routines currently use fixed parameters as noted. The correction of (detector pixel-to-pixel) correction can be switched on by the appropriate flag. It is strongly recommended to use only the small-scale correction. The large-scale variant is a bit over-aggressive and deprecated. The correction of detector-level badpixels can also be switched on with a flag. This will interpolate over badpixels to substitute their values instead of relying on dithering.

#### 3.3.1.8.6 Products:

| Name | Type | Description |
|------|------|-------------|
|------|------|-------------|

| Name             | Type            | Description                                    |
|------------------|-----------------|------------------------------------------------|
| IFS_ SCIENCE_ DR | FITS[Incube(4)] | The reduced science data as a wavelength cube. |

### 3.3.1.9 sph\_ifs\_detector\_persistence

#### 3.3.1.9.1 Purpose:

Measure the detector persistence.

#### 3.3.1.9.2 Input frames:

| Data Type (TAG)                            | Source      | Optional | Min | Max |
|--------------------------------------------|-------------|----------|-----|-----|
| IFS_ DETECTOR_ PERSISTENCE_ OFF_ RAW       | Raw data    | No       | 2   | Any |
| IFS_ DETECTOR_ PERSISTENCE_ ON_ SAT_ RAW   | Raw data    | No       | 1   | Any |
| IFS_ DETECTOR_ PERSISTENCE_ ON_ UNSAT_ RAW | Raw data    | No       | 1   | Any |
| IFS_ MASTER_ DARK                          | Calibration | Yes      | 0   | 1   |
| IFS_ STATIC_ BADPIXELMAP                   | Calibration | Yes      | 0   | 1   |

#### 3.3.1.9.3 Raw frame keywords used:

| Keyword | Type   | Optional | Description                        |
|---------|--------|----------|------------------------------------|
| DATE    | string | No       | The creation date of the raw file. |

#### 3.3.1.9.4 Parameters:

| Name                                            | Type   | Description                                                                                                                                                                                       | Default                           | Allowed vals. |
|-------------------------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------|---------------|
| ifs.detector_persistence.outfilename            | string | The output filename for the product. Please also see the esorex documentation for naming of output products.                                                                                      | ifs_detector_persistence_map.fits | -             |
| ifs.detector_persistence.fitorder               | int    | The order of the fit to use. Note that a fitorder > 2 can give unstable fitting results.                                                                                                          | 2                                 | 1-40          |
| ifs.detector_persistence.coll_alg               | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean.                                                                                                                              | 1                                 | 0,1,2         |
| ifs.detector_persistence.clean_mean.reject_high | int    | The clean mean reject pixels on high end.                                                                                                                                                         | 0                                 | 0-20          |
| ifs.detector_persistence.clean_mean.reject_low  | int    | The clean mean reject pixels on low end.                                                                                                                                                          | 0                                 | 0-20          |
| ifs.detector_persistence.threshold_upper        | double | The threshold for detection of illuminated regions. All regions with pixels above this value in the unsaturated image (with lamp on) are masked as illuminated regions in all other input frames. | 40000.0                           | -             |

| Name                                             | Type   | Description                                                                                                                                                                         | Default | Allowed vals. |
|--------------------------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------|
| ifs.detector_<br>persistence.threshold_<br>lower | double | The threshold for detection of dark regions. All regions with pixels below this value in the unsaturated image (with lamp on) are masked as dark regions in all other input frames. | 1000.0  | -             |

#### 3.3.1.9.5 Description:

This recipe determines the detector persistence, by measuring the signal fall-off rate. The input raw frameset should contain frames taken with the illumination source on as well as off. Specifically, there should be at least one exposure containing a significant number of saturated pixels, at least one exposure containing illuminated (but not saturated pixels) and exposures with the source switched off. The exposures with illumination off should be taken in rapid succession immediately after the source is turned off. Frames are ordered in time sequence by the recipe, optionally a hotpixel mask from a master dark or a separate image is used to mask bad pixels. As a first step, a simple thresholding algorithm is used on the illuminated but **unsaturated** image to determine illuminated and unilluminated pixel sets,  $P_i$  and  $P_u$ . For each of the unilluminated frames, the mean for the unilluminated pixels  $\langle P_u \rangle$  is subtracted from the mean of the illuminated pixels giving  $P(t) = \langle P_i \rangle(t) - \langle P_u \rangle(t)$ . The series of  $P(t)$  values is then fit assuming a polynomial behaviour in  $1/t$ , that is, assuming  $P(t) = c_0 + c_1 \times 1/t + c_2 \times 1/t^2 + \dots$ . Up to which coefficient the fit is to be performed is set using the fitorder user parameter. A copy of the input illuminated but not saturated frame is saved as the main recipe product. The relevant persistence measurements are written as keywords into the product header.

#### 3.3.1.9.6 Products:

| Name                         | Type            | Description                                                                                                                                                                                                                                                |
|------------------------------|-----------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IFS_DETECTOR_<br>PERSISTENCE | FITS[Imcube(4)] | A FITS cube with the fitting coefficients for each pixel. The fitting coefficients are for a polynomial fit of log(count) vs. log(time). Each plane in the image cube contains the values of one polynomial coefficient (starting with the constant term). |

#### 3.3.1.10 sph\_ifs\_cal\_background

##### 3.3.1.10.1 Purpose:

Measure the instrument background.

##### 3.3.1.10.2 Input frames:

| Data Type (TAG)        | Source      | Optional | Min | Max |
|------------------------|-------------|----------|-----|-----|
| IFS_CAL_BACKGROUND_RAW | Raw data    | No       | 1   | Any |
| IFS_MASTER_DARK        | Calibration | Yes      | 0   | 1   |

##### 3.3.1.10.3 Raw frame keywords used:

none

### 3.3.1.10.4 Parameters:

| Name                                                  | Type   | Description                                                                                                                                                                                               | Default                                 | Allowed vals. |
|-------------------------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------|---------------|
| ifs.cal_<br>background.outfilename                    | string | This parameter sets the filename that the product will be written out as.<br>Please also see the esorex documentation about filename of products                                                          | ifs_cal_<br>background_<br>map.fits     | -             |
| ifs.cal_<br>background.fit_<br>filename               | string | This parameter sets the filename that the product will be written out as.<br>Please also see the esorex documentation about filename of products                                                          | ifs_cal_<br>background_map_<br>fit.fits | -             |
| ifs.cal_<br>background.coll_<br>alg                   | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean.                                                                                                                                      | 2                                       | 0,1,2         |
| ifs.cal_<br>background.clean_<br>mean.reject_<br>high | int    | The number of pixels to reject when combining frames at the high end.<br>Number of input frames must be > reject_high + reject_low!                                                                       | 1                                       | 0-20          |
| ifs.cal_<br>background.clean_<br>mean.reject_<br>low  | int    | The number of pixels to reject when combining frames at the low end.<br>Number of input frames must be > reject_high + reject_low!                                                                        | 1                                       | 0-20          |
| ifs.cal_<br>background.sigma_<br>clip                 | double | The sigma clipping value for static badpixel detection. Default is 5.0. @                                                                                                                                 | 5.0                                     | 0.0-200.0     |
| ifs.cal_<br>background.fit                            | bool   | Flag to switch polynomial fitting on/off.                                                                                                                                                                 | 0                                       | -             |
| ifs.cal_<br>background.fitorder                       | int    | The fitting order to use for the 2D polynomial fitting. Only used if the fit option is set to TRUE.                                                                                                       | 10                                      | 0-30          |
| ifs.cal_<br>background.smooth                         | double | Smoothing length to smooth the combined image. The value gives the FWHM of the gaussian that the combined image is convolved with to smooth it. Set the value to zero to switch smoothing off completely. | 0.0                                     | 0.0-2000.0    |
| ifs.cal_<br>background.nsamples                       | int    | The number of samples to use for a polynomial 2D fit. Only used if the fit parameter is set.                                                                                                              | 1000                                    | 0-1000000     |

### 3.3.1.10.5 Description:

This recipe creates a summed, optionally dark subtracted frame that is mainly useful for background measurements. The raw input frames must carry the IFS\_CAL\_BACKGROUND\_RAW tag. The dark frame is optional and will be subtracted from the resulting frame if provided. Static badpixels are determined using the sigma\_clip user parameter – an OR combination is used with the badpixels in the master dark frame if one is provided. The resulting background map is divided by the exposure time to give a result in counts per second. If a dark was provided the exposure time of this dark is subtracted from the total exposure time before. In case the smoothing parameter is set to a value above 0, the resulting combined frame is smoothed (after all badpixels have been interpolated). If so desired, a 2D polynomial fit to the measured (possibly smoothed) background is also written out as a second product.

### 3.3.1.10.6 Products:

| Name                      | Type        | Description                                                                                                                                                       |
|---------------------------|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IFS_ CAL_ BACKGROUND      | FITS[Im(4)] | The total background. The frame is saved as a 4 extension FITS file with image, badpixels, rms and weightmap. The file gives the counts/seconds for each pixel.   |
| IFS_ CAL_ BACKGROUND_ FIT | FITS[Im(4)] | The total fitted background. The frame is saved as a 4 extension FITS file with image, badpixels, rms and weightmap. The units are counts/seconds for each pixel. |

### 3.3.1.11 sph\_ifs\_distortion\_map

#### 3.3.1.11.1 Purpose:

Measure the lenslet array distortion

#### 3.3.1.11.2 Input frames:

| Data Type (TAG)           | Source      | Optional | Min | Max |
|---------------------------|-------------|----------|-----|-----|
| IFS_ DISTORTION_ MAP_ RAW | Raw data    | No       | 1   | 500 |
| IFS_ MASTER_ DFF_ LONG1   | Calibration | Yes      | 0   | 1   |
| IFS_ MASTER_ DFF_ LONG2   | Calibration | Yes      | 0   | 1   |
| IFS_ MASTER_ DFF_ LONG3   | Calibration | Yes      | 0   | 1   |
| IFS_ MASTER_ DFF_ LONG4   | Calibration | Yes      | 0   | 1   |
| IFS_ MASTER_ DFF_ LONGBB  | Calibration | Yes      | 0   | 1   |
| IFS_ MASTER_ DFF_ SHORT   | Calibration | Yes      | 0   | 1   |
| IFS_ IFU_ FLAT_ FIELD     | Calibration | Yes      | 0   | 1   |
| IFS_ CAL_ BACKGROUND      | Calibration | Yes      | 0   | 1   |
| IFS_ MASTER_ DARK         | Calibration | Yes      | 0   | 1   |
| IFS_ STATIC_ BADPIXELMAP  | Calibration | Yes      | 0   | 1   |
| IFS_ WAVECALIB            | Calibration | No       | 1   | 1   |
| IFS_ POINT_ PATTERN       | Calibration | Yes      | 0   | 1   |
| IFS_ PREAMP_ FLAT         | Calibration | Yes      | 0   | 1   |

#### 3.3.1.11.3 Raw frame keywords used:

| Keyword            | Type   | Optional | Description                                         |
|--------------------|--------|----------|-----------------------------------------------------|
| ESO INS2 DITH POSX | double | Yes      | The dithering position in X for the frame in pixels |
| ESO INS2 DITH POSY | double | Yes      | The dithering position in Y for the frame in pixels |

#### 3.3.1.11.4 Parameters:

| Name                                 | Type   | Description                                                                                                  | Default                        | Allowed vals. |
|--------------------------------------|--------|--------------------------------------------------------------------------------------------------------------|--------------------------------|---------------|
| ifs.distortion_ map.outfilename      | string | The output filename for the product. Please also see the esorex documentation for naming of output products. | ifs_ distortion_ map.fits      | -             |
| ifs.distortion_ map.ldt_ outfilename | string | The filename of the wavelength cube output. This is mainly for debugging purposes.                           | ifs_ distortion_ map_ ldt.fits | -             |

| Name                                               | Type   | Description                                                                                                                                                                                                                                                                                                   | Default                          | Allowed vals. |
|----------------------------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|---------------|
| ifs.distortion_<br>map.coll_ alg                   | int    | The collapse algorithm to use. 0 = Mean, 1 = Median, 2 = Clean mean                                                                                                                                                                                                                                           | 1                                | 0,1,2         |
| ifs.distortion_<br>map.clean_<br>mean.reject_ high | int    | The clean mean reject pixels on high end.                                                                                                                                                                                                                                                                     | 0                                | 0-20          |
| ifs.distortion_<br>map.clean_<br>mean.reject_ low  | int    | The clean mean reject pixels on low end.                                                                                                                                                                                                                                                                      | 0                                | 0-20          |
| ifs.distortion_<br>map.point_ table_<br>filename   | string | The output filename for the point pattern table. Please also see the esorex documentation for naming of output products.                                                                                                                                                                                      | distortion_ point_<br>table.fits | -             |
| ifs.distortion_<br>map.dither                      | bool   | Controls the use of dithering.                                                                                                                                                                                                                                                                                | 0                                | -             |
| ifs.distortion_<br>map.threshold                   | double | The threshold (sigma) for detecting the grind point sources.                                                                                                                                                                                                                                                  | 3.0                              | 0.0-200.0     |
| ifs.distortion_<br>map.fitting_ order              | int    | The fitting order of the 2D polynomial fit to the distortions.                                                                                                                                                                                                                                                | 3                                | 2-8           |
| ifs.distortion_<br>map.max_ distortion             | double | The maximum distortion to accept. Points above this value are removed before polynomial fitting.                                                                                                                                                                                                              | 4.0                              | 0.0-2000.0    |
| ifs.distortion_<br>map.self_ check                 | bool   | Flag to set when a consistency self check is needed. An output is created containing the reduced input frames with the distortion map applied. Setting this option will double the execution time of this recipe!                                                                                             | 0                                | -             |
| ifs.distortion_<br>map.add_ rotation               | double | Additional rotation angle that the measured point pattern is rotated by before attempting a match. This is applied in addition to the rotations specified in the lenslet model in the keywords of the calibration input files. The sense of direction is specified in the same sense as in the lenslet model. | 0.0                              | -360.0-360.0  |

### 3.3.1.11.5 Description:

This recipe measures the distortion of the lenslet grid. The input raw frames are first reduced in the same way as for the science\_dr recipe (allowing dither but no frame rotation), optionally including dark subtraction via either a master background or a master dark and optionally (if all flats provided) flat fielding. The resulting monochromatic images are then collapsed along the wavelength direction giving a single image. This image is then analysed to detect the point sources using simple thresholding, taking the user parameter as the threshold value (sigmas). Now the way the recipe proceeds depends on the inputs. If no input point pattern has been provided, the recipe will construct one from the reduced images detected point sources. This will then be written out as a product. If a input point pattern was provided, the recipe will skip this step and proceed directly to the measurement of the distortion. Please note that the distortion is measured in any case which means that the output distortion should be zero in case that no input point pattern was provided. The distortion map is constructed by comparing the detected point sources position with the expected point source position as provided in the input point pattern. Each comparison is done with the closest point found and yields one distortion vector. Upon

completion, all distortion vectors that have a length larger than the max\_distortion specified as a user parameter will be removed before the x and y components of the distortion vectors will be fit with a 2D polynomial (of the user specified fitting order). To allow for easier quality control, the recipe provides a user flag for a self consistency check. If this flag is set, the recipe will now apply the measured distortion map to the input raw data and calculate any residual distortion left. This residual is written out as an extra FITS file – it should be visually inspected to verify that the distortion map has been calculated with sufficient accuracy in the detector region(s) of interest.

### 3.3.1.11.6 Products:

| Name               | Type        | Description                                                                                                                                                                                                                                                                                                                 |
|--------------------|-------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IFS_POINT_PATTERN  | FITS[Table] | The point pattern as obtained from the input images. Only written in case that an input point pattern was provided. This product may be used as reference input for future runs of this recipe.                                                                                                                             |
| IFS_DISTORTION_MAP | FITS[Im(8)] | The distortion map. The distortion map is saved as an 8 extension FITS file with the first 4 extensions containing the distortion in the x direction, the badpixels, the rms on the distortion in x and a weightmap. The second set of 4 extensions contain the same information but for the distortion in the y direction. |

## 3.3.2 IFS Workflow Summary

The IFS workflow is summarized in Fig.3.5

## 3.3.3 IFS Special Notes

The IFS calibration cascade is currently under heavy revision. It is thus actually not recommended to draw information on the actual workflow from this version of the manual! the individual recipe descriptions above are up to date and accurate, but the overall workflow will change considerably over the next weeks!

## 3.4 ZIMPOL

ZIMPOL offers the following basic observing modes:

- Imaging
- P1 polarimetry
- P23 polarimetry

These have their own science recipes and a number of dedicated calibrations. Additionally, ZIMPOL has different operational modes:



- FastPol
- SlowPol
- Window

These do not affect the choice or the order of the calibration workflow, but data taken in any of these sub-modes should not be mixed with data from other sub-modes in a single cascade!

### 3.4.1 ZIMPOL Imaging Calibrations and Science

These are calibration that apply to the IMAGING mode of ZIMPOL.

#### 3.4.1.1 sph\_zpl\_preproc\_imaging

##### 3.4.1.1.1 Purpose:

Pre-processing of the zimpol raw data, imaging mode (utility recipe).

##### 3.4.1.1.2 Input frames:

| Data Type (TAG)         | Source   | Optional | Min | Max |
|-------------------------|----------|----------|-----|-----|
| ZPL_PREPROC_IMAGING_RAW | Raw data | No       | 1   | Any |

#### 3.4.1.1.3 Raw frame keywords used:

| Keyword              | Type   | Optional | Description                                       |
|----------------------|--------|----------|---------------------------------------------------|
| ESO DET READ CURNAME | string | Yes      | KEYWORD NAME for the Detector Read Mode           |
| ESO DET OUT1 X       | int    | Yes      | KEYWORD NAME for X location of output, camera-1   |
| ESO DET OUT1 Y       | int    | Yes      | KEYWORD NAME for Y location of output, camera-1   |
| ESO DET OUT1 NX      | int    | Yes      | Output-1 data pixels in X, camera-1               |
| ESO DET OUT1 NY      | int    | Yes      | Output-1 data pixels in Y, camera-1               |
| ESO DET OUT1 OVSCX   | int    | Yes      | Output overscan pixels in X, camera-1             |
| ESO DET OUT1 OVSCY   | int    | Yes      | Output-1 overscan pixels in Y, camera-1           |
| ESO DET OUT1 PRSCX   | int    | Yes      | Output-1 prescan pixels in X, camera-1            |
| ESO DET OUT1 PRSCY   | int    | Yes      | Output-1prescan pixels in Y, camera-1             |
| ESO DET OUT2 X       | int    | Yes      | KEYWORD NAME for X location of output 2, camera-1 |
| ESO DET OUT2 Y       | int    | Yes      | KEYWORD NAME for Y location of output 2, camera-1 |
| ESO DET OUT2 NX      | int    | Yes      | Output-2 data pixels in X, camera-1               |
| ESO DET OUT2 NY      | int    | Yes      | Output 2 data pixels in Y, camera-1               |
| ESO DET OUT2 OVSCX   | int    | Yes      | Output 2 overscan pixels in X, camera-1           |
| ESO DET OUT2 OVSCY   | int    | Yes      | Output-2 overscan pixels in Y, camera-1           |
| ESO DET OUT2 PRSCX   | int    | Yes      | Output-2 prescan pixels in X, camera-1            |
| ESO DET OUT2 PRSCY   | int    | Yes      | Output-2 prescan pixels in Y, camera-1            |
| ESO DET OUT1 X       | int    | Yes      | KEYWORD NAME for X location of output, camera-2   |
| ESO DET OUT1 Y       | int    | Yes      | KEYWORD NAME for Y location of output, camera-2   |
| ESO DET OUT1 NX      | int    | Yes      | Output-1 data pixels in X, camera-2               |
| ESO DET OUT1 OVSCX   | int    | Yes      | Output-1 overscan pixels in X, camera-2           |
| ESO DET OUT1 OVSCY   | int    | Yes      | Output-1 prescan pixels in Y, camera-2            |
| ESO DET OUT1 PRSCX   | int    | Yes      | Output-1 prescan pixels in X, camera-2            |
| ESO DET OUT1 PRSCY   | int    | Yes      | Output-1 prescan pixels in Y, camera-2            |
| ESO DET OUT2 X       | int    | Yes      | KEYWORD NAME for X location of output, camera-2   |
| ESO DET OUT2 Y       | int    | Yes      | KEYWORD NAME for Y location of output, camera-2   |
| ESO DET OUT2 NX      | int    | Yes      | Output-2 data pixels in X, camera-2               |
| ESO DET OUT2 NY      | int    | Yes      | Output-2 data pixels in Y, camera-2               |
| ESO DET OUT2 OVSCX   | int    | Yes      | Output 2 overscan pixels in X, camera-2           |
| ESO DET OUT2 OVSCY   | int    | Yes      | Output-2 overscan pixels in Y, camera-2           |
| ESO DET OUT2 PRSCX   | int    | Yes      | Output-2 prescan pixels in X, camera-2            |
| ESO DET OUT2 PRSCY   | int    | Yes      | Output-2 prescan pixels in Y, camera-2            |

#### 3.4.1.1.4 Parameters:

| Name                                         | Type   | Description                                                             | Default                          | Allowed vals. |
|----------------------------------------------|--------|-------------------------------------------------------------------------|----------------------------------|---------------|
| zpl.preproc_<br>imaging.outfilename_<br>cam1 | string | The output postfix-filename of the pre-processed raw data for CAMERA-1. | preproc_ imaging_<br>cam_ 1.fits | -             |
| zpl.preproc_<br>imaging.outfilename_<br>cam2 | string | The output postfix-filename of the pre-processed raw data for CAMERA-2. | preproc_ imaging_<br>cam_ 2.fits | -             |

#### 3.4.1.1.5 Description:

This recipe performs pre-processing steps for the raw data in the imaging modes. The pre-

processing is an utility recipe and should be only used by off-line data reduction. The raw frame cube in the imaging mode is two extensions fits-files with the following format:

- first extension represents data cube of NDITS frames from camera-1 for a given DIT, including overscan area of 2 ADUs;
- second extention represents data cube of NDITS zimpol frames from camera-2 for a given DIT, including overscan area of 2 ADUs.

No other frame is used in this recipe. In the imaging detector mode each raw frame contains 2-interlaced sub-frames, but the useful imaging component is only kept in the first sub-frame because the second one is masked (it can be considered as a dark current). The input raw cube frame, which should carry SPH\_ZPL\_TAG\_PREPROC\_IMAGING\_RAW tag, are read first and then the following pre-processing steps are performed:

1. extract each camera from the each extension (»two camera cubes«);
2. combine the 2 detector segments (ADU) into a single image »trim away« prescan/overscan areas;
3. split into even and odd sub-frames;
4. for each initial raw image create a plane with two extensions (informative component - intensity, dark current);
5. create an output fits files with two images extension and one binary table extension with the computed mean values of the overscan bias level and its rms (4 cols).

Since the zimpol frame is square, splitting the two sub-frames yields to the 1:2 aspect ratio. The pre-processing imaging output product is written out in the two fits-cube files (camera-1 and camera-2) with the ZPL EXP IMAGING format specified as follows:

- odd sub-frame image (informative component);
- even sub-frame image (dark current component);
- table of mean overscan bias level values and its rms (4 cols):
  - [1-col, 2-col] ADU1 OVSC MEAN & ADU1 OVSC RMS
  - [3-col, 4-col] ADU2 OVSC MEAN & ADU2 OVSC RMS

These pre-processing imaging products may be used in all subsequent imaging recipes.

#### 3.4.1.1.6 Products:

| Name | Type | Description |
|------|------|-------------|
|------|------|-------------|

| Name                  | Type              | Description                                                                                                                                                                                                                                                                                                         |
|-----------------------|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ PREPROC_ IMAGING | FITS[Im(2),Bt(1)] | The output product is two fits-cube files with 3 extensions (for camera-1 and camera-2) of the ZPL EXP IMAGING format specified as follows: - odd sub-frame image; - sub-frame image; table of mean overscan bias level values and its rms (4 cols): - ADU1 OVSC MEAN, ADU1 OVSC RMS, ADU2 OVSC MEAN, ADU2 OVSC RMS |

### 3.4.1.2 sph\_zpl\_master\_bias\_imaging

#### 3.4.1.2.1 Purpose:

Create master bias, imaging mode.

#### 3.4.1.2.2 Input frames:

| Data Type (TAG)                   | Source      | Optional | Min | Max |
|-----------------------------------|-------------|----------|-----|-----|
| ZPL_ BIAS_ IMAGING_ RAW           | Raw data    | Yes      | 0   | Any |
| ZPL_ BIAS_ IMAGING_ PREPROC       | Calibration | Yes      | 0   | Any |
| ZPL_ BIAS_ IMAGING_ PREPROC_ CAM1 | Calibration | Yes      | 0   | Any |
| ZPL_ BIAS_ IMAGING_ PREPROC_ CAM2 | Calibration | Yes      | 0   | Any |

#### 3.4.1.2.3 Raw frame keywords used:

| Keyword              | Type   | Optional | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|----------------------|--------|----------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ESO DRS PC PROD TYPE | string | No       | This keyword is mandatory if the pre-processed data are used. As the format of the zimpol data is complicated, this keyword is introduced in order to guarantee that the input frames are imaging pre-processed data, produced by the sph_zpl_preproc recipe which added this keyword automatically. The value of this keyword is set up to >>SPH PC PREPROC ZPL EXP IMAGING<<. Note: if raw data are used (default), then all keywords needed for the pre-processing recipe (see sph_zpl_preproc_imaging) must be presented in the raw data. |

#### 3.4.1.2.4 Parameters:

| Name                                        | Type   | Description                                                                                                                     | Default                               | Allowed vals. |
|---------------------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------|---------------------------------------|---------------|
| zpl.master_ bias_ imaging.outfilename       | string | The output filename for the product for the camera-1/2. Please also see the esorex documentation for naming of output products. | zpl_ master_ bias_ imaging.fits       | -             |
| zpl.master_ bias_ imaging.outfilename_ cam1 | string | The output filename for the product for the camera-2. Please also see the esorex documentation for naming of output products.   | zpl_ master_ bias_ imaging_ cam1.fits | -             |



| Name                                                    | Type   | Description                                                                                                                                                                 | Default                           | Allowed vals. |
|---------------------------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------|---------------|
| zpl.master_bias_imaging.outfilename_cam2                | string | The output filename for the product for the camera-2. Please also see the esorex documentation for naming of output products.                                               | zpl_master_bias_imaging_cam2.fits | -             |
| zpl.master_bias_imaging.subtract_overscan               | bool   | Flag to set if the overscan mean values must be subtracted from pre-processed data (TRUE) Note that this parameter is applied if pre-processed data containt overscan table | 1                                 | -             |
| zpl.master_bias_imaging.coll_alg                        | int    | Set the collapse algorithm. The available algorithms: 0 = Mean, 1 = Median, 2 = Clean Mean. Default is 2 = Clean Mean                                                       | 2                                 | 0,1,2         |
| zpl.master_bias_imaging.coll_alg.clean_mean.reject_high | int    | The number of pixels to reject when combining frames at the high end. Number of input frames must be > reject_high + reject_low                                             | 0                                 | 0-20          |
| zpl.master_bias_imaging.coll_alg.clean_mean.reject_low  | int    | The number of pixels to reject when combining frames at the low end. Number of input frames must be > reject_high + reject_low                                              | 0                                 | 0-20          |
| zpl.master_bias_imaging.clean_mean.sigma                | double | The number of pixels to reject when combining frames in sigma from median. NOT SUPPORTED YET!                                                                               | 5.0                               | 0.0-200.0     |
| zpl.master_bias_imaging.sigma_clip                      | double | The sigma clipping value for static badpixel detection. Default is 0 (no sigma clipping).                                                                                   | 0.0                               | 0.0-200.0     |
| zpl.master_bias_imaging.keep_intermediate               | bool   | Flag to set if intermediate data must be saved, namely pre-processed and overscan pre-processed subtracted data                                                             | 0                                 | -             |
| zpl.preproc.outfilename_cam1                            | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-1.                                                                                   | preproc_cam1.fits                 | -             |
| zpl.preproc.outfilename_cam2                            | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-2.                                                                                   | preproc_cam2.fits                 | -             |

#### 3.4.1.2.5 Description:

This recipe creates the master bias calibration frame for the imaging mode. The input frames might be either bias raw frames with the ZPL\_BIAS\_IMAGING\_RAW tag or pre-processed bias frames, which should carry the ZPL\_BIAS\_IMAGING\_PREPROC\_CAM1 and/or ZPL\_BIAS\_IMAGING\_PREPROC\_CAM2 tags. No other frames are used in this recipe. If input frames are raw frames then the master bias recipe first performs the pre-processing step for all input frames (raw cubes), creating corresponding pre-processed frames (cubes) for both ZIMPOL cameras (see also sph\_zpl\_preproc\_imaging for the detailed description of the pre-processing). The master bias for each camera is then created by combining pre-processed frames (= all planes) from the imaging pre-processed cube(s) using a specified collapse algorithm (usually the clean\_mean algorithm, defined as a default one). If the flag >>subtract\_overscan<< is not set up to 0, the recipe subtracts (before combining) the overscan bias level from the pre-processed cube(s) individually for each plane. Otherwise, the overscan subtraction step is skipped. (The overscan bias level - >>ADU1 mean overscan value<< from the left area of the image and

>>ADU2 mean overscan value<< from the right area of the image – for odd and even sub-frames are saved anyway as a binary table in the imaging pre-processed cube(s)). After all pre-processed frames (all 4 zimpol exposure sub-frames) are combined in this way, the badpixel maps are determined on the result, using a simple sigma clipping algorithm. It sets the bad/hot pixels to be all those that are further than the >>specified sigma x the total RMS<< of the whole image away from the image median. The resulting master dark frames for both cameras are written out in the DOUBLE IMAGE (8 extensions) format specified as follows:

1. odd sub-frame (informative component):
  - master bias image,
  - badpixel-map,
  - ncomb-map,
  - rms-map;
2. even sub-frame (dark current component):
  - master bias image,
  - badpixel-map,
  - ncomb-map,
  - rms-map.

Note that the default parameter for the sigma clipping >>sigma\_clip<< is set up to 0. In this case the recipe will not detect >>hot/bad pixels<<, so all pixels will be considered as good ones in the product. Usually, the zpl exposure imaging frames have the two vertical pixel stripes with strong >>bias<< signal. If the >>sigma\_clip<< parameter is not 0, these pixels will be detected as bad ones and will be excluded from the subsequent treatment in the sphere pipeline (according to the sphere pipeline concept the detected bad pixel is marked as a bad in the badpixel-map and its rms value set to the 1e10 in the rms-map). Therefore, using the master bias for all subsequent imaging recipes in the default case (no sigma clipping), will preserve the signal in the vertical pixels stripes. The master imaging bias products are used in all subsequent imaging recipes.

#### 3.4.1.2.6 Products:

| Name                          | Type        | Description                                                                                                                                                                                                                                                                                                                        |
|-------------------------------|-------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ MASTER_<br>BIAS_ IMAGING | FITS[Im(8)] | The resulting master bias frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions (2 master frames), grouped by the following order: odd sub-frame master bias image (informative), badpixel-map, ncomb-map and rms-map; even sub-frame master bias image (dark current), badpixel-map, ncomb-map and rms-map; |

| Name                         | Type        | Description                                                                                                                                                                                                                                                                                                                        |
|------------------------------|-------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_MASTER_BIAS_IMAGING_CAM1 | FITS[Im(8)] | The resulting master bias frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions (2 master frames), grouped by the following order: odd sub-frame master bias image (informative), badpixel-map, ncomb-map and rms-map; even sub-frame master bias image (dark current), badpixel-map, ncomb-map and rms-map; |
| ZPL_MASTER_BIAS_IMAGING_CAM2 | FITS[Im(8)] | The resulting master bias frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions (2 master frames), grouped by the following order: odd sub-frame master bias image (informative), badpixel-map, ncomb-map and rms-map; even sub-frame master bias image (dark current), badpixel-map, ncomb-map and rms-map; |

### 3.4.1.3 sph\_zpl\_master\_dark\_imaging

#### 3.4.1.3.1 Purpose:

Create master dark, imaging mode.

#### 3.4.1.3.2 Input frames:

| Data Type (TAG)               | Source      | Optional | Min | Max |
|-------------------------------|-------------|----------|-----|-----|
| ZPL_DARK_IMAGING_RAW          | Raw data    | Yes      | 0   | Any |
| ZPL_DARK_IMAGING_PREPROC      | Calibration | Yes      | 0   | Any |
| ZPL_DARK_IMAGING_PREPROC_CAM1 | Calibration | Yes      | 0   | Any |
| ZPL_DARK_IMAGING_PREPROC_CAM2 | Calibration | Yes      | 0   | Any |
| ZPL_MASTER_BIAS_IMAGING       | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_IMAGING_CAM1  | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_IMAGING_CAM2  | Calibration | Yes      | 0   | 1   |

#### 3.4.1.3.3 Raw frame keywords used:

| Keyword              | Type   | Optional | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|----------------------|--------|----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ESO DRS PC PROD TYPE | string | No       | This keyword is mandatory if pre-processed data are used. As the format of the zimpol data is complicated, this keyword is introduced in order to guarantee that the input frames are imaging pre-processed data, produced by the sph_zpl_preproc recipe which added this keyword automatically. The value of this keyword is set up to >>SPH PC PREPROC ZPL EXP IMAGING<<. Note: if raw data are used (default), then all keywords needed for the pre-processing recipe (see sph_zpl_preproc_imaging) must be presented in the raw data. |

#### 3.4.1.3.4 Parameters:

| Name                                                         | Type   | Description                                                                                                                                                                 | Default                               | Allowed vals. |
|--------------------------------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------|---------------|
| zpl.master_ dark_ imaging.outfilename                        | string | The output filename for the product for the camera-1/2. Please also see the esorex documentation for naming of output products.                                             | zpl_ master_ dark_ imaging.fits       | -             |
| zpl.master_ dark_ imaging.outfilename_ cam1                  | string | The output filename for the product for the camera-1. Please also see the esorex documentation for naming of output products.                                               | zpl_ master_ dark_ imaging_ cam1.fits | -             |
| zpl.master_ dark_ imaging.outfilename_ cam2                  | string | The output filename for the product for the camera-2. Please also see the esorex documentation for naming of output products.                                               | zpl_ master_ dark_ imaging_ cam2.fits | -             |
| zpl.master_ dark_ imaging.subtract_ overscan                 | bool   | Flag to set if the overscan mean values must be subtracted from pre-processed data (TRUE) Note that this parameter is applied if pre-processed data containt overscan table | 1                                     | -             |
| zpl.master_ dark_ imaging.coll_ alg                          | int    | Set the collapse algorithm. The available algorithms: 0 = Mean, 1 = Median, 2 = Clean Mean. Default is 2 = Clean Mean                                                       | 2                                     | 0,1,2         |
| zpl.master_ dark_ imaging.coll_ alg.clean_ mean.reject_ high | int    | The number of pixels to reject when combining frames at the high end. Number of input frames must be > reject_ high +reject_ low                                            | 0                                     | 0-20          |
| zpl.master_ dark_ imaging.coll_ alg.clean_ mean.reject_ low  | int    | The number of pixels to reject when combining frames at the low end. Number of input frames must be > reject_ high +reject_ low                                             | 0                                     | 0-20          |
| zpl.master_ dark_ imaging.clean_ mean.sigma                  | double | The number of pixels to reject when combining frames in sigma from median. NOT SUPPORTED YET!                                                                               | 5.0                                   | 0.0-200.0     |
| zpl.master_ dark_ imaging.sigma_ clip                        | double | The sigma clipping value for static badpixel detection. Default is 0 (=inf).                                                                                                | 0.0                                   | 0.0-200.0     |
| zpl.master_ dark_ imaging.keep_ intermediate                 | bool   | Flag to set if intermediate date must be saved, namely pre-processed and overscan pre-processed subtracted data                                                             | 0                                     | -             |
| zpl.preproc.outfilename_ cam1                                | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-1.                                                                                   | preproc_ cam1.fits                    | -             |
| zpl.preproc.outfilename_ cam2                                | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-2.                                                                                   | preproc_ cam2.fits                    | -             |

#### 3.4.1.3.5 Description:

This recipe creates master dark calibration frames for the imaging modes. The input frames might be either dark raw frames with the ZPL\_DARK\_IMAGING\_RAW tag or pre-processed dark frames, which should carry the ZPL\_DARK\_IMAGING\_PREPROC\_CAM1 and/or

ZPL\_DARK\_IMAGING\_PREPROC\_CAM2 tags, and master bias frames (if any) with the ZPL\_MASTER\_BIAS\_IMAGING\_CAM1 and/or ZPL\_MASTER\_BIAS\_IMAGING\_CAM2 tags. If input frames are raw frames then the master dark recipe first performs the pre-processing step for all input frames (raw cubes), creating corresponding pre-processed frames (cubes) for both ZIMPOL cameras (see also sph\_zpl\_preproc\_imaging for the detailed description of the pre-processing step). The master imaging dark for each camera is then created by combining pre-processed frames (= all planes) from imaging pre-processed cube(s) using a specified collapse algorithm (usually the clean\_mean algorithm, defined as a default one). If the flag >>subtract\_overscan<< is not set up to 0, the recipe subtracts (before combining) the overscan bias level from the pre-processed cube(s) individually for each plane. Otherwise, the overscan subtraction step is skipped. (The overscan bias level – >>ADU1 mean overscan value<< from the left area of the image and >>ADU2 mean overscan value<< from the right area of the image – for odd and even sub-frames are saved anyway as a binary table in the imaging pre-processed cube(s)). After all pre-processed frames (all 2 zimpol imaging exposure sub-frames) are combined in this way, the badpixel maps are determined on the results, using a simple sigma clipping algorithm. It sets the bad/hot pixels to be all those that are further than the >>specified sigma x the total RMS<< of the whole image away from the image median. The resulting master dark imaging frames for both cameras are subtracted by the corresponding master bias imaging calibrations and written out in the DOUBLE IMAGE (8 extensions) format specified as follows:

1. odd sub-frame (informative component):
  - master dark image,
  - badpixel-map,
  - ncomb-map,
  - rms-map;
2. even sub-frame (dark current component):
  - master dark image,
  - badpixel-map,
  - ncomb-map,
  - rms-map.

The master imaging dark products are used in the all subsequent imaging recipes.

#### 3.4.1.3.6 Products:

| Name                    | Type        | Description                                                                                                                                                                                                                                                                                                                          |
|-------------------------|-------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_MASTER_DARK_IMAGING | FITS[Im(8)] | The resulting master dark frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions (2 master frames), grouped by the following order: - odd sub-frame master dark image (informative), badpixel-map, ncomb-map and rms-map; - even sub-frame master dark image (dark current), badpixel-map, rms-map and rms-map. |

| Name                         | Type        | Description                                                                                                                                                                                                                                                                                                                            |
|------------------------------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_MASTER_DARK_IMAGING_CAM1 | FITS[Im(8)] | The resulting master dark frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions (2 master frames), grouped by the following order: - odd sub-frame master dark image (informative), badpixel-map, ncomb-map and rms-map; - even sub-frame master dark image (dark current), badpixel-map, rms-map and rms-map.   |
| ZPL_MASTER_DARK_IMAGING_CAM2 | FITS[Im(8)] | The resulting master dark frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions (2 master frames), grouped by the following order: - odd sub-frame master dark image (informative), badpixel-map, ncomb-map and rms-map; - even sub-frame master dark image (dark current), badpixel-map, ncomb-map and rms-map. |

#### 3.4.1.4 sph\_zpl\_intensity\_flat\_imaging

##### 3.4.1.4.1 Purpose:

Create intensity flat field, imaging mode.

##### 3.4.1.4.2 Input frames:

| Data Type (TAG)                         | Source      | Optional | Min | Max |
|-----------------------------------------|-------------|----------|-----|-----|
| ZPL_INT_FLAT_FIELD_IMAGING_RAW          | Raw data    | Yes      | 0   | Any |
| ZPL_INT_FLAT_FIELD_IMAGING_PREPROC_RAW  | Raw data    | Yes      | 0   | Any |
| ZPL_INT_FLAT_FIELD_IMAGING_PREPROC_CAM1 | Calibration | Yes      | 0   | Any |
| ZPL_INT_FLAT_FIELD_IMAGING_PREPROC_CAM2 | Calibration | Yes      | 0   | Any |
| ZPL_MASTER_BIAS_IMAGING                 | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_IMAGING_CAM1            | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_IMAGING_CAM2            | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_IMAGING                 | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_IMAGING_CAM1            | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_IMAGING_CAM2            | Calibration | Yes      | 0   | 1   |
| ZPL_STATIC_BADPIXELMAP_IMAGING          | Calibration | Yes      | 0   | 1   |
| ZPL_STATIC_BADPIXELMAP_IMAGING_CAM1     | Calibration | Yes      | 0   | 1   |
| ZPL_STATIC_BADPIXELMAP_IMAGING_CAM2     | Calibration | Yes      | 0   | 1   |

#### 3.4.1.4.3 Raw frame keywords used:

| Keyword              | Type   | Optional | Description                                                                                                                                                                                                                                                                                                                                                                             |
|----------------------|--------|----------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ESO DRS PC PROD TYPE | string | No       | This keyword is mandatory if the pre-processed data are used. As the format of the zimpol data is complicated, this keyword is introduced in order to guarantee that the input frames are imaging pre-processed data, produced by the sph_zpl_preproc_imaging recipe which added this keyword automatically. The value of this keyword is set up to >>SPH PC PREPROC ZPL EXP IMAGING<<. |

#### 3.4.1.4.4 Parameters:

| Name                                                | Type   | Description                                                                                                                                                                                       | Default                                                     | Allowed vals. |
|-----------------------------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------|---------------|
| zpl.intensity_ flat_ imaging.outfilename            | string | The output filename for the product, camera-1/2. Please also see the esorex documentation for naming of output products.                                                                          | zpl_ intensity_ flat_ imaging.fits                          | -             |
| zpl.intensity_ flat_ imaging.outfilename_ cam1      | string | The output filename for the product, camera-1. Please also see the esorex documentation for naming of output products.                                                                            | zpl_ intensity_ flat_ imaging_ cam1.fits                    | -             |
| zpl.intensity_ flat_ imaging.outfilename_ cam2      | string | The output filename for the product, camera-2. Please also see the esorex documentation for naming of output products.                                                                            | zpl_ intensity_ flat_ imaging_ cam2.fits                    | -             |
| zpl.intensity_ flat_ imaging.subtract_ overscan     | bool   | Flag to set if the overscan mean values must be subtracted from pre-processed data (TRUE) Note that this parameter is applied if pre-processed data containt overscan table                       | 1                                                           | -             |
| zpl.intensity_ flat_ imaging.badpixfilename         | string | Controls the filename of the badpixel map, if requested for output. Ignored if make_ badpix is FALSE.                                                                                             | zpl_ intensity_ flat_ imaging_ nonlin_ badpixels.fits       | -             |
| zpl.intensity_ flat_ imag- ing.badpixfilename_ cam1 | string | Controls the filename of the badpixel map, if requested for output. Ignored if make_ badpix is FALSE.                                                                                             | zpl_ intensity_ flat_ imaging_ nonlin_ badpixels_ cam1.fits | -             |
| zpl.intensity_ flat_ imag- ing.badpixfilename_ cam2 | string | Controls the filename of the badpixel map, if requested for output. Ignored if make_ badpix is FALSE.                                                                                             | zpl_ intensity_ flat_ imaging_ nonlin_ badpixels_ cam2.fits | -             |
| zpl.intensity_ flat_ imaging.robust_ fit            | bool   | Controls if fitting method is to be a robust linear fit. This will reduce the effect of cosmic rays and other temporary bad pixels. See e.g. Numerical Recipes for a description of the algorithm | 0                                                           | -             |



| Name                                                       | Type   | Description                                                                                                                                                        | Default      | Allowed vals. |
|------------------------------------------------------------|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|---------------|
| zpl.intensity_flat_imaging.collapse                        | bool   | Controls if the collapse is used to calculate intensity flat instead of the fitting                                                                                | 1            | -             |
| zpl.intensity_flat_imaging.coll_alg                        | int    | Set the collapse algorithm. The available algorithms: 0 = Mean, 1 = Median, 2 = Clean Mean. Default is 2 = Clean Mean                                              | 2            | 0,1,2         |
| zpl.intensity_flat_imaging.coll_alg.clean_mean.reject_high | int    | The number of pixels to reject when combining frames at the high end. Number of input frames must be > reject_high + reject_low                                    | 0            | 0-20          |
| zpl.intensity_flat_imaging.coll_alg.clean_mean.reject_low  | int    | The number of pixels to reject when combining frames at the low end. Number of input frames must be > reject_high + reject_low                                     | 0            | 0-20          |
| zpl.intensity_flat_imaging.sigma_clip                      | double | The sigma clipping value for static badpixel detection. Default is 5.                                                                                              | 5.0          | 0.0-200.0     |
| zpl.intensity_flat_imaging.badpix_lowtolerance             | double | Threshold value for linearity badpixels. All pixels that have a flat field (slope) below this value will be flagged as bad.                                        | 0.1          | -             |
| zpl.intensity_flat_imaging.badpix_uptolerance              | double | Threshold value for linearity badpixels. All pixels that have a flat field (slope) above this value will be flagged as bad.                                        | 10.0         | -             |
| zpl.intensity_flat_imaging.badpix_chisqtolerance           | double | Threshold value for linearity badpixels. All pixels that have chi-squared value for the linear fit that is above this value will be flagged as bad                 | 50.0         | -             |
| zpl.intensity_flat_imaging.keep_intermediate               | bool   | Flag to set if intermediate data must be saved, namely pre-processed and overscan pre-processed subtracted data, linbadpix map and non-normalized products (FALSE) | 0            | -             |
| zpl.preproc.outfilename_cam1                               | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-1.                                                                          | preproc_cam1 | -             |
| zpl.preproc.outfilename_cam2                               | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-2.                                                                          | preproc_cam2 | -             |

#### 3.4.1.4.5 Description:

The recipe creates the intensity flat field calibration frames for the imaging modes. The input frames might be either intensity flat raw frames with the ZPL\_INT\_FLAT\_IMAGING\_RAW tag or pre-processed intensity flat frames, which should carry the ZPL\_INT\_FLAT\_IMAGING\_PREPROC\_CAM1 and/or ZPL\_INT\_FLAT\_IMAGING\_PREPROC\_CAM2 tags, and master bias frames (if any) with the ZPL\_MASTER\_BIAS\_IMAGING\_CAM1 and/or ZPL\_MASTER\_BIAS\_IMAGING\_CAM2 tags, and and master dark frames (if any) with the ZPL\_MASTER\_DARK\_IMAGING\_CAM1 and/or ZPL\_MASTER\_DARK\_IMAGING\_CAM2 tags. If input frames are raw frames then the intensity flat field recipe first performs the pre-processing step for all input frames (raw cubes), creating corresponding pre-processed frames (cubes) for both ZIMPOL cameras (see also sph\_zpl\_preproc\_imaging for the detailed description of the pre-processing step). There are two

main different methods to calculate the master intensity flatfield:

- combining frames (plus normalizing): in this case, the raw frames must be acquired with the same DIT and filter;
- linear fitting method of the individual pixels: in this case, the raw frames must be acquired either with a different DIT or with a different intensity of the lamp, but with the same filter.

The first <combining frames method> combines pre-processed raw intensity flatfield frame (= all planes) from the pre-processed cube(s) using the specified collapse algorithm (usually the `clean_mean` algorithm, defined as a default one). After all pre-processed frames (all 4 zimpol exposure sub-frames) are combined in this way, the badpixel maps are determined on the results, using a simple sigma clipping algorithm. It sets the bad/hot pixels to be all those that are further than the  $>>\text{specified sigma} \times \text{the total RMS}<<$  of the whole image away from the image median. Note that the badpixels that are stored in the master flat field itself as produced by this recipe contain all the badpixels (for each sub-frames individually) at this point in the cascade (i.e. badpixels from the master dark and master bias, if exists). The resulting master intensity flat field products for both cameras are then written out in the fits files in the DOUBLE IMAGE format:

1. zpl exp imaging odd sub-frame (informative component):
  - intensity flat field image,
  - badpixel-map,
  - ncomb-map,
  - rms-map;
2. zpl exp imaging even sub-frame (dark current component):
  - intensity flat field image
  - badpixel-map
  - ncomb-map
  - rms-map;

The second <linear fitting flat fielding procedure> described below (identical to that for the IFS and IRDIS) is then applied to the each  $>>\text{zpl exp imaging sub-frames}<<$  ( odd - informative component, even-dark current component) seperately.

1. The mean value is determined for the respective sub-frame for all exposures.
2. For every pixel  $p = (x, y)$ , a set of  $m_i, v_i(x, y)$  data pairs are stored with  $m_i$  being the exposure mean value and  $v_i(x, y)$  being the pixel value for exposure  $i$ .
3. The flat field value is defined as the slope  $c_i$  of a linear fit  $F$  to the data  $m_i, v_i$ .
4. The fit itself is performed either using a maximum likelihood method or a robust fitting method which minimizes the sum of the absolute value of the deviations rather than the sum of the squares of the deviations (see e.g. Numerical Recipes for the algorithm). The robust fitting method will yield better results when significant outliers (e.g. due to cosmic rays) can be expected.
5. The flat field values (linear coefficients) are saved as an image as the main product of the recipe in the same DOUBLE IMAGE format (see above).

Additionally, the recipe may also produce a separate output of all pixels that are identified as non-linear. The criteria for non-linearity are set by the user parameters and can be either pixels that have a flat field value outside specified bounds and/or pixels for which the linear fit produces a reduced chi-squared above a given threshold value. For reliable non-linearity flagging using the reduced chi-squared it is necessary to use many high quality input exposures. Since the badpixel treatment is somewhat complicated, some important points: the badpixels that are stored in the master flat field itself as produced by this recipe contain all the badpixels (for each sub-frames individually) at this point in the cascade. Pixels that were marked as bad from the input static badpixel map are also marked as bad here. The optional static badpixel output that is produced contains strictly only those pixel that the flat field recipe itself deemed to be bad. This does not necessarily include all the badpixels from the static badpixel input file. The intensity flat field calibration products for both cameras may be used in all subsequent imaging mode recipes if one needs to remove the pixel to pixel variation of the signal response on the detector.

#### 3.4.1.4.6 Products:

| Name                            | Type        | Description                                                                                                                                                                                                                                                                                                                                                                    |
|---------------------------------|-------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_INT_FLAT_FIELD_IMAGING      | FITS[Im(8)] | The resulting intensity imaging flat field frame is of the DOUBLE IMAGE format. This DOUBLE IMAGE frame contains 8 image extensions (2 master frames), grouped by the following: odd sub-frame intensity flat field image (informative), badpixel-map, rms-map and weight-map; even sub-frame intensity flat field image (dark current), badpixel-map, rms-map and weight-map. |
| ZPL_INT_FLAT_FIELD_IMAGING_CAM1 | FITS[Im(8)] | The resulting intensity imaging flat field frame is of the DOUBLE IMAGE format. This DOUBLE IMAGE frame contains 8 image extensions (2 master frames), grouped by the following: odd sub-frame intensity flat field image (informative), badpixel-map, rms-map and weight-map; even sub-frame intensity flat field image (dark current), badpixel-map, rms-map and weight-map. |
| ZPL_INT_FLAT_FIELD_IMAGING_CAM2 | FITS[Im(8)] | The resulting intensity imaging flat field frame is of the DOUBLE IMAGE format. This DOUBLE IMAGE frame contains 8 image extensions (2 master frames), grouped by the following: odd sub-frame intensity flat field image (informative), badpixel-map, rms-map and weight-map; even sub-frame intensity flat field image (dark current), badpixel-map, rms-map and weight-map. |

| Name                                    | Type        | Description                                                                                                                                                                                                                                                                                    |
|-----------------------------------------|-------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_NON_LINEAR_BADPIXELMAP_IMAGING      | FITS[Im(4)] | Optional output of all the non-linear pixels determined. All pixels as determined in this recipe using the <code>zpl.intensity_flat.badpix_low(up)tolerance</code> parameters. This badpixel map frame is of ZPL EXP IMAGING format: odd sub-frame image; even sub-frame image (dark current). |
| ZPL_NON_LINEAR_BADPIXELMAP_IMAGING_CAM1 | FITS[Im(4)] | Optional output of all the non-linear pixels determined. All pixels as determined in this recipe using the <code>zpl.intensity_flat.badpix_low(up)tolerance</code> parameters. This badpixel map frame is of ZPL EXP IMAGING format: odd sub-frame image; even sub-frame image (dark current). |
| ZPL_NON_LINEAR_BADPIXELMAP_IMAGING_CAM2 | FITS[Im(4)] | Optional output of all the non-linear pixels determined. All pixels as determined in this recipe using the <code>zpl.intensity_flat.badpix_low(up)tolerance</code> parameters. This badpixel map frame is of ZPL EXP IMAGING format: odd sub-frame image; even sub-frame image (dark current). |

### 3.4.1.5 sph\_zpl\_star\_center\_img

#### 3.4.1.5.1 Purpose:

Determine the center of the star center frame, imaging mode.

#### 3.4.1.5.2 Input frames:

| Data Type (TAG)                  | Source      | Optional | Min | Max |
|----------------------------------|-------------|----------|-----|-----|
| ZPL_STAR_CENTER_IMG_RAW          | Raw data    | Yes      | 0   | Any |
| ZPL_STAR_CENTER_IMG_PREPROC      | Calibration | Yes      | 0   | Any |
| ZPL_STAR_CENTER_IMG_PREPROC_CAM1 | Calibration | Yes      | 0   | Any |
| ZPL_STAR_CENTER_IMG_PREPROC_CAM2 | Calibration | Yes      | 0   | Any |
| ZPL_MASTER_BIAS_IMAGING          | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_IMAGING_CAM1     | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_IMAGING_CAM2     | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_IMAGING          | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_IMAGING_CAM1     | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_IMAGING_CAM2     | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_IMAGING       | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_IMAGING_CAM1  | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_IMAGING_CAM2  | Calibration | Yes      | 0   | 1   |

### 3.4.1.5.3 Raw frame keywords used:

| Keyword              | Type   | Optional | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|----------------------|--------|----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ESO DRS PC PROD TYPE | string | No       | <p>This keyword is mandatory if the pre-processed data are used. As the format of the zimpol data is complicated, this keyword is introduced in order to guarantee that the input frames are imaging pre-processed data, produced by the sph_zpl_preproc_imaging recipe which added this keyword automatically. The value of this keyword is set up to &gt;&gt;SPH PC PREPROC ZPL EXP IMAGING&lt;&lt;. Note: if raw data are used (default), then all keywords needed for the pre-processing recipe (see sph_zpl_preproc_imaging) must be presented in the raw data.</p> <p>SPH_COMMON_KEYWORD_CAM1_DITHERING_X<br/> double 0 0 100.0 X-position of the arm1(camera-1) [pix]<br/> SPH_COMMON_KEYWORD_CAM1_DITHERING_Y<br/> double 0 0 100.0 Y-position of the arm1(camera-1) [pix]<br/> SPH_COMMON_KEYWORD_CAM2_DITHERING_X<br/> double 0 0 100.0 X-position of the arm2(camera-2) [pix]<br/> SPH_COMMON_KEYWORD_CAM2_DITHERING_Y<br/> double 0 0 100.0 Y-position of the arm2(camera-2) [pix]</p> |

### 3.4.1.5.4 Parameters:

| Name                                 | Type   | Description                                                                                                                                                                 | Default                       | Allowed vals. |
|--------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|---------------|
| zpl.star_center_img.outfilename      | string | The output filename for the product, camera-1/2. Please also see the esorex documentation for naming of output products.                                                    | zpl_star_center_img.fits      | -             |
| zpl.star_center_img.outfilename_cam1 | string | The output filename for the product, camera-1. Please also see the esorex documentation for naming of output products.                                                      | zpl_star_center_img_cam1.fits | -             |
| zpl.star_center_img.outfilename_cam2 | string | The output filename for the product, camera2. Please also see the esorex documentation for naming of output products.                                                       | zpl_star_center_img_cam2.fits | -             |
| zpl.science_p1.subtract_overscan     | bool   | Flag to set if the overscan mean values must be subtracted from pre-processed data (TRUE) Note that this parameter is applied if pre-processed data containt overscan table | 1                             | -             |
| zpl.star_center_img.coll_alg         | int    | Set the collapse algorithm. The available algorithms: 0 = Mean, 1 = Median. Default is 0 = Mean.                                                                            | 0                             | 0,1           |

| Name                                  | Type   | Description                                                                                                                                                                                                                                                                                                       | Default           | Allowed vals. |
|---------------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|---------------|
| zpl.star_center_img.filter_radius     | double | Filter radius for the frame combination. A non zero value leads to suppression of high frequencies in the fourier domain before frame combination. The value expresses the minimum unsuppressed frequency as fraction of total frequency domain radius (a value of 1 would suppress essentially all frequencies). | 0.0               | 0.0-1.0       |
| zpl.star_center_img.sigma             | double | The sigma threshold to use for source detections                                                                                                                                                                                                                                                                  | 10.0              | -             |
| zpl.star_center_img.unsharp_window    | int    | Before finding centres an unsharp algorithm is used on the image. This specifies the window width for the mask in pixels.                                                                                                                                                                                         | 4                 | -             |
| zpl.star_center_img.keep_intermediate | bool   | Flag to set if intermediate data must be saved, namely pre-processed and overscan pre-processed subtracted data, linbadpix map and non-normalized products (FALSE)                                                                                                                                                | 0                 | -             |
| zpl.star_center_img.save_interprod    | bool   | Flag to set if the field center table must be saved as intermediate product (FALSE) Note that this parameter must be only applied for the offline pipeline                                                                                                                                                        | 0                 | -             |
| zpl.preproc.outfilename_cam1          | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-1.                                                                                                                                                                                                                         | preproc_cam1.fits | -             |
| zpl.preproc.outfilename_cam2          | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-2.                                                                                                                                                                                                                         | preproc_cam2.fits | -             |

#### 3.4.1.5.5 Description:

The recipe determines the position of star centers for the imaging modes. The input frames might be either science imaging raw frames with the ZPL\_STAR\_CENTER\_IMG\_RAW tag or pre-processed science imaging frames, which should carry the ZPL\_STAR\_CENTER\_IMG\_PREPROC\_CAM1 and/or ZPL\_STAR\_CENTER\_IMG\_PREPROC\_CAM2 tags, and master bias frames (if any) with the ZPL\_MASTER\_BIAS\_IMAGING\_CAM1 and/or ZPL\_MASTER\_BIAS\_IMAGING\_CAM2 tags, and and master dark frames (if any) with the ZPL\_MASTER\_DARK\_IMAGING\_CAM1 and/or ZPL\_MASTER\_DARK\_IMAGING\_CAM2 tags, and intensity flat field frames (if any) with the ZPL\_INT\_FLAT\_IMAGING\_CAM1 and/or ZPL\_INT\_FLAT\_IMAGING\_CAM2 tags. If input frames are raw frames, then the recipe first performs the pre-processing step for all input frames (raw cubes), creating corresponding pre-processed frames (cubes) for both ZIMPOL cameras (see also sph\_zpl\_preproc\_imaging for the detailed description of the pre-processing step). The pre-processed star center frames are then calibrated (for each camera) by subtracting the master imaging bias and the master imaging dark, and divided by the corresponding intensity imaging flat field. The calibrated frames are de-dithered and then saved as intermediate products. The next step is to combine all these calibrated and de-dithered frames, using a standard mean algorithm. The combined frames for both cameras are of the DOUBLE IMAGE (8 extensions) format specified as follows: - combined intensity star-center image, badpixel-map, ncomb-map and rms-map. - combined star-center dark image (dark current), badpixel-map, ncomb-map and rms-map. The combined star center frame is then analysed using an aperture detection

algorithm: - The aperture detection algorithm detects all connected regions of at least 4 pixels size (area) that are the given sigma above the background. - The so detected waffle stars are then used to construct a geometric centre of all stars found. This is then the frame centre. The recipe also works for the case that there is only one star (e.g. the coronagraph is out and no waffle stars are formed). The coordinates of the detected frame centers are added as the keywords in the header of the output fits-file products for each camera: - DRS ZPL STAR CENTER IFRAME XCOORD; - DRS ZPL STAR CENTER IFRAME YCOORD; - DRS ZPL STAR CENTER PFRAME XCOORD; - DRS ZPL STAR CENTER PFRAME YCOORD. This star center calibrated products for each camera should be used in the science imaging recipe.

#### 3.4.1.5.6 Products:

| Name                         | Type        | Description                                                                                                                                                                                                                                                             |
|------------------------------|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ STAR_ CENTER_ IMG       | FITS[Im(8)] | The final combined star center frame of the DOUBLE IMAGING format. This frame contains 8 image extensions: - combined intensity image, badpixel-map, ncomb-map and rms-map; - combined dark image (dark current), badpixel-map, ncomb-map and rms-map.                  |
| ZPL_ STAR_ CENTER_ IMG_ CAM1 | FITS[Im(8)] | The final combined star center frame of the DOUBLE IMAGING format for the camera-1. This frame contains 8 image extensions: - combined intensity image, badpixel-map, ncomb-map and rms-map; - combined dark image (dark current), badpixel-map, ncomb-map and rms-map. |
| ZPL_ STAR_ CENTER_ IMG_ CAM2 | FITS[Im(8)] | The final combined star center frame of the DOUBLE IMAGING format for the camera-2. This frame contains 8 image extensions: - combined intensity image, badpixel-map, ncomb-map and rms-map; - combined dark image (dark current), badpixel-map, ncomb-map and rms-map. |

#### 3.4.1.6 sph\_zpl\_science\_imaging

##### 3.4.1.6.1 Purpose:

Reduce science frames in the imaging modes.

#### 3.4.1.6.2 Input frames:

| Data Type (TAG)                  | Source      | Optional | Min | Max |
|----------------------------------|-------------|----------|-----|-----|
| ZPL_SCIENCE_IMAGING_RAW          | Raw data    | Yes      | 0   | Any |
| ZPL_SCIENCE_IMAGING_PREPROC_RAW  | Raw data    | Yes      | 0   | Any |
| ZPL_SCIENCE_IMAGING_PREPROC_CAM1 | Calibration | Yes      | 0   | Any |
| ZPL_SCIENCE_IMAGING_PREPROC_CAM2 | Calibration | Yes      | 0   | Any |
| ZPL_MASTER_BIAS_IMAGING          | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_IMAGING_CAM1     | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_IMAGING_CAM2     | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_IMAGING          | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_IMAGING_CAM1     | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_IMAGING_CAM2     | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_IMAGING       | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_IMAGING_CAM1  | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_IMAGING_CAM2  | Calibration | Yes      | 0   | 1   |
| ZPL_STAR_CENTER_IMG_CAM1         | Calibration | Yes      | 0   | 1   |
| ZPL_STAR_CENTER_IMG_CAM2         | Calibration | Yes      | 0   | 1   |
| ZPL_STAR_CENTER_IMG              | Calibration | Yes      | 0   | 1   |
| ZPL_FIELD_CENTER_TABLE           | Calibration | Yes      | 0   | Any |
| ZPL_FILTER_TABLE                 | Calibration | Yes      | 0   | 1   |
| ZPL_PHOT_STAR_TABLE              | Calibration | Yes      | 0   | 1   |

#### 3.4.1.6.3 Raw frame keywords used:

| Keyword              | Type   | Optional | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|----------------------|--------|----------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ESO DRS PC PROD TYPE | string | No       | <p>This keyword is mandatory if the pre-processed data are used. As the format of the zimpol data is complicated, this keyword is introduced in order to guarantee that the input frames are imaging pre-processed data, produced by the sph_zpl_preproc_imaging recipe which added this keyword automatically. The value of this keyword is set up to &gt;&gt;SPH PC PREPROC ZPL EXP IMAGING&lt;&lt;. Note: if raw data are used (default), then all keywords needed for the pre-processing recipe (see sph_zpl_preproc_imaging) must be presented in the raw data.</p> <p>SPH_COMMON_KEYWORD_CAM1_DITHERING_X<br/> double 0 0 100.0 X-position of the arm1(camera-1) [pix]<br/> SPH_COMMON_KEYWORD_CAM1_DITHERING_Y<br/> double 0 0 100.0 Y-position of the arm1(camera-1) [pix]<br/> SPH_COMMON_KEYWORD_CAM2_DITHERING_X<br/> double 0 0 100.0 X-position of the arm2(camera-2) [pix]<br/> SPH_COMMON_KEYWORD_CAM2_DITHERING_Y<br/> double 0 0 100.0 Y-position of the arm2(camera-2) [pix]<br/> SPH_COMMON_KEYWORD_DROT2_MODE string<br/> 0 0 0 De-rotator mode: ELEV(pupil stabilized),<br/> SKY(field stabilized)</p> |

#### 3.4.1.6.4 Parameters:

| Name                                             | Type   | Description                                                                                                                                                                                                                                                                                                       | Default                           | Allowed vals. |
|--------------------------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------|---------------|
| zpl.science_<br>imaging.outfilename              | string | The output filename for the product, camera-1/2. Please also see the esorex documentation for naming of output products.                                                                                                                                                                                          | zpl_science_<br>imaging.fits      | -             |
| zpl.science_<br>imaging.outfilename_<br>cam1     | string | The output filename for the product, camera-1. Please also see the esorex documentation for naming of output products.                                                                                                                                                                                            | zpl_science_<br>imaging_cam1.fits | -             |
| zpl.science_<br>imaging.outfilename_<br>cam2     | string | The output filename for the product, camera2. Please also see the esorex documentation for naming of output products.                                                                                                                                                                                             | zpl_science_<br>imaging_cam2.fits | -             |
| zpl.science_<br>imaging.subtract_<br>overscan    | bool   | Flag to set if the overscan mean values must be subtracted from pre-processed data (TRUE) Note that this parameter is applied if pre-processed data containt overscan table                                                                                                                                       | 1                                 | -             |
| zpl.science_<br>imaging.coll_ alg                | int    | Set the collapse algorithm. The available algorithms: 0 = Mean, 1 = Median. Default is 0 = Mean.                                                                                                                                                                                                                  | 0                                 | 0,1           |
| zpl.science_<br>imaging.filter_ radius           | double | Filter radius for the frame combination. A non zero value leads to suppression of high frequencies in the fourier domain before frame combination. The value expresses the minimum unsuppressed frequency as fraction of total frequency domain radius (a value of 1 would suppress essentially all frequencies). | 0.0                               | 0.0-1.0       |
| zpl.science_<br>imaging.keep_<br>intermediate    | bool   | Flag to set if intermediate data must be saved, namely pre-processed and overscan pre-processed subtracted data, linbadpix map and non-normalized products (FALSE)                                                                                                                                                | 0                                 | -             |
| zpl.science_<br>imaging.save_ interprod          | bool   | Flag to set if the field center table must be saved as intermediate product (FALSE) Note that this parameter must be only applied for the offline pipeline                                                                                                                                                        | 0                                 | -             |
| zpl.science_<br>imaging.star_ center_<br>iframe  | bool   | Flag to set if only the center coordinates of the iframe from the star center calibration frame should be used as a center coordinates to de-rotate iframe and pframe[dark current] (TRUE)                                                                                                                        | 1                                 | -             |
| zpl.science_<br>imaging.center_<br>xoffset_ cam1 | double | X-offset from the center of the image for the camera-1                                                                                                                                                                                                                                                            | 0.0                               | -512.0-512.0  |
| zpl.science_<br>imaging.center_<br>yoffset_ cam1 | double | Y-offset from the center of the image for the camera-1                                                                                                                                                                                                                                                            | 0.0                               | -512.0-512.0  |



| Name                                    | Type   | Description                                                                                                                                                                                                                                                                                                                       | Default           | Allowed vals. |
|-----------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|---------------|
| zpl.science_imaging.center_xoffset_cam2 | double | X-offset from the center of the image for the camera-2                                                                                                                                                                                                                                                                            | 0.0               | -512.0-512.0  |
| zpl.science_imaging.center_yoffset_cam2 | double | Y-offset from the center of the image for the camera-2                                                                                                                                                                                                                                                                            | 0.0               | -512.0-512.0  |
| zpl.science_imaging.star_r              | double | The star radius [arcsecond] used for the Strehl ratio estimate. A negative value disables the estimation. When AO is enabled and 0 (default) is provided 2 arcseconds are used. When AO is disabled and 0 is provided a radius corresponding to 500 PIXEL is used. This option is ignored in absence of a ZPL_FILTER_TABLE frame. | 0.0               | -             |
| zpl.science_imaging.bg_r1               | double | The internal radius [arcsecond] of the background used for the Strehl ratio estimate. When AO is enabled and 0 (default) is provided 2 arcseconds are used. When AO is disabled and 0 is provided a radius corresponding to 500 PIXEL is used. This option is ignored in absence of a ZPL_FILTER_TABLE frame.                     | 0.0               | -             |
| zpl.science_imaging.bg_r2               | double | The external radius [arcsecond] of the background used for the Strehl ratio estimate. When AO is enabled and 0 (default) is provided 3 arcseconds are used. When AO is disabled and 0 is provided a radius corresponding to all the PIXELS in the image is used. This option is ignored in absence of a ZPL_FILTER_TABLE frame.   | 0.0               | -             |
| zpl.preproc.outfilename_cam1            | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-1.                                                                                                                                                                                                                                         | preproc_cam1.fits | -             |
| zpl.preproc.outfilename_cam2            | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-2.                                                                                                                                                                                                                                         | preproc_cam2.fits | -             |

#### 3.4.1.6.5 Description:

The recipe reduces combined science frames for the imaging modes. The input frames might be either science imaging raw frames with the ZPL\_SCIENCE\_IMAGING\_RAW tag or pre-processed science imaging frames, which should carry the ZPL\_SCIENCE\_IMAGING\_PREPROC\_CAM1 and/or ZPL\_SCIENCE\_IMAGING\_PREPROC\_CAM2 tags, and master bias frames (if any) with the ZPL\_MASTER\_BIAS\_IMAGING\_CAM1 and/or ZPL\_MASTER\_BIAS\_IMAGING\_CAM2 tags, and master dark frames (if any) with the ZPL\_MASTER\_DARK\_IMAGING\_CAM1 and/or ZPL\_MASTER\_DARK\_IMAGING\_CAM2 tags, and intensity flat field frames (if any) with the ZPL\_INT\_FLAT\_IMAGING\_CAM1 and/or ZPL\_INT\_FLAT\_IMAGING\_CAM2 tags. If input frames are raw frames, the science imaging recipe first performs the pre-processing

step for all input frames (raw cubes), creating corresponding pre-processed frames (cubes) for both ZIMPOL cameras (see also sph\_zpl\_preproc\_imaging for the detailed description of the pre-processing step). The pre-processed imaging science frames are then calibrated (for each camera) by subtracting the master imaging bias and the master imaging dark, and divided by the corresponding intensity imaging flat field. The calibrated frames are de-dithered and de-rotated and then saved as intermediate products. Note: the calibration frames with SPH\_ZPL\_TAG\_STAR\_CENTER\_IMG\_CALIB\_CAM1(CAM2) tags provide the center coordinates to rotate around. If these calibrations are not presented the center of the frames will be used (normally, xc=yc=512 pixel). The final step is to combine all these calibrated, de-dithered and de-rotated frames, using a standard mean algorithm. The combined frames for both cameras are of the DOUBLE IMAGE (8 extensions) format specified as follows: - combined intensity science image, badpixel-map, ncomb-map and rms-map. - combined science dark image (dark current), badpixel-map, ncomb-map and rms-map. The output double image frames are reduced pipeline data products for both cameras. Some additional notes:

- For a point-source an estimate of the Strehl ratio may be useful. The presence of a filter table frame will enable the estimation, which on failure will do nothing and on success will insert Strehl related QC parameters for both cameras into the product headers related to the second camera.

#### 3.4.1.6.6 Products:

| Name                                 | Type        | Description                                                                                                                                                                                                                                                                  |
|--------------------------------------|-------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ SCIENCE_ IMAGING_ REDUCED       | FITS[Im(8)] | The resulting reduced science imaging frame of the DOUBLE IMAGING format for the camera-1. This frame contains 8 image extensions: - science intensity image, badpixel-map, ncomb-map and rms-map; - science dark image (dark current), badpixel-map, ncomb-map and rms-map. |
| ZPL_ SCIENCE_ IMAGING_ REDUCED_ CAM1 | FITS[Im(8)] | The resulting reduced science imaging frame of the DOUBLE IMAGING format for the camera-1. This frame contains 8 image extensions: - science intensity image, badpixel-map, ncomb-map and rms-map; - science dark image (dark current), badpixel-map, ncomb-map and rms-map. |
| ZPL_ SCIENCE_ IMAGING_ REDUCED_ CAM2 | FITS[Im(8)] | The resulting reduced science imaging frame of the DOUBLE IMAGING format for the camera-2. This frame contains 8 image extensions: - science intensity image, badpixel-map, ncomb-map and rms-map; - science dark image (dark current), badpixel-map, ncomb-map and rms-map. |

## 3.4.2 ZIMPOL Polarimetry Calibrations and Science

### 3.4.2.1 sph\_zpl\_preproc

#### 3.4.2.1.1 Purpose:

Pre-processing of the zimpol raw data, polarimetric modes (utlity recipe).

#### 3.4.2.1.2 Input frames:

| Data Type (TAG)   | Source   | Optional | Min | Max |
|-------------------|----------|----------|-----|-----|
| ZPL_ PREPROC_ RAW | Raw data | No       | 1   | Any |

#### 3.4.2.1.3 Raw frame keywords used:

| Keyword              | Type   | Optional | Description                                       |
|----------------------|--------|----------|---------------------------------------------------|
| ESO DET READ CURNAME | string | Yes      | KEYWORD NAME for the Detector Read Mode           |
| ESO DET OUT1 X       | int    | Yes      | KEYWORD NAME for X location of output, camera-1   |
| ESO DET OUT1 Y       | int    | Yes      | KEYWORD NAME for Y location of output, camera-1   |
| ESO DET OUT1 NX      | int    | Yes      | Output-1 data pixels in X, camera-1               |
| ESO DET OUT1 NY      | int    | Yes      | Output-1 data pixels in Y, camera-1               |
| ESO DET OUT1 OVSCX   | int    | Yes      | Output overscan pixels in X, camera-1             |
| ESO DET OUT1 OVSCY   | int    | Yes      | Output-1 overscan pixels in Y, camera-1           |
| ESO DET OUT1 PRSCX   | int    | Yes      | Output-1 prescan pixels in X, camera-1            |
| ESO DET OUT1 PRSCY   | int    | Yes      | Output-1prescan pixels in Y, camera-1             |
| ESO DET OUT2 X       | int    | Yes      | KEYWORD NAME for X location of output 2, camera-1 |
| ESO DET OUT2 Y       | int    | Yes      | KEYWORD NAME for Y location of output 2, camera-1 |
| ESO DET OUT2 NX      | int    | Yes      | Output-2 data pixels in X, camera-1               |
| ESO DET OUT2 NY      | int    | Yes      | Output 2 data pixels in Y, camera-1               |
| ESO DET OUT2 OVSCX   | int    | Yes      | Output 2 overscan pixels in X, camera-1           |
| ESO DET OUT2 OVSCY   | int    | Yes      | Output-2 overscan pixels in Y, camera-1           |
| ESO DET OUT2 PRSCX   | int    | Yes      | Output-2 prescan pixels in X, camera-1            |
| ESO DET OUT2 PRSCY   | int    | Yes      | Output-2 prescan pixels in Y, camera-1            |
| ESO DET OUT1 X       | int    | Yes      | KEYWORD NAME for X location of output, camera-2   |
| ESO DET OUT1 Y       | int    | Yes      | KEYWORD NAME for Y location of output, camera-2   |
| ESO DET OUT1 NX      | int    | Yes      | Output-1 data pixels in X, camera-2               |
| ESO DET OUT1 OVSCX   | int    | Yes      | Output-1 overscan pixels in X, camera-2           |
| ESO DET OUT1 OVSCY   | int    | Yes      | Output-1 prescan pixels in Y, camera-2            |
| ESO DET OUT1 PRSCX   | int    | Yes      | Output-1 prescan pixels in X, camera-2            |
| ESO DET OUT1 PRSCY   | int    | Yes      | Output-1 prescan pixels in Y, camera-2            |
| ESO DET OUT2 X       | int    | Yes      | KEYWORD NAME for X location of output, camera-2   |
| ESO DET OUT2 Y       | int    | Yes      | KEYWORD NAME for Y location of output, camera-2   |
| ESO DET OUT2 NX      | int    | Yes      | Output-2 data pixels in X, camera-2               |
| ESO DET OUT2 NY      | int    | Yes      | Output-2 data pixels in Y, camera-2               |
| ESO DET OUT2 OVSCX   | int    | Yes      | Output 2 overscan pixels in X, camera-2           |
| ESO DET OUT2 OVSCY   | int    | Yes      | Output-2 overscan pixels in Y, camera-2           |
| ESO DET OUT2 PRSCX   | int    | Yes      | Output-2 prescan pixels in X, camera-2            |
| ESO DET OUT2 PRSCY   | int    | Yes      | Output-2 prescan pixels in Y, camera-2            |

#### 3.4.2.1.4 Parameters:

| Name                         | Type   | Description                                                             | Default            | Allowed vals. |
|------------------------------|--------|-------------------------------------------------------------------------|--------------------|---------------|
| zpl.preproc.outfilename_cam1 | string | The output postfix-filename of the pre-processed raw data for CAMERA-1. | preproc_cam_1.fits | -             |
| zpl.preproc.outfilename_cam2 | string | The output postfix-filename of the pre-processed raw data for CAMERA-2. | preproc_cam_2.fits | -             |

#### 3.4.2.1.5 Description:

This recipe performs pre-processing steps for the raw data in the polarimetric modes. The pre-processing is an utility recipe and should be only used by off-line data reduction! The raw frame in the polarimetric modes are two extensions fits-file format:

- first extension represents data cube of NDITS frames from camera-1 for a given DIT, including prescan /overscan area of 2 ADUs;
- second extension represents data cube of NDITS zimpol frames from camera-2 for a given DIT, including prescan / overscan area of 2 ADUs.

No other frame is used in this recipe. In all polarimetric ZIMPOL modes (P1,P2,P3) detector mode is always double-phase mode. In the double-phase detector mode one single ZIMPOL-exposure is output of two consecutive images/frames from one CCD:

- the 1 image is the k-th ZIMPOL frame recorded at phase one=Phase 0
- the 2 image is the k+1 ZIMPOL frame recorded at phase one=Phase PI

Each frame contains 2-interlaced sub-frames, storing 2 complimentary polarization component images. The input raw cube frame should carry SPH\_ZPL\_TAG\_PREPROC\_RAW tag is read first and then the following pre-processing steps are performed:

1. extract each camera from the each extension («two camera cubes»);
2. combine the 2 detector segments (ADU) into a single image »trim away« prescan/overscan areas from images;
3. compute the mean overscan bias level from the overscan areas;
4. cut junk rows for Phase 0 (one bottom and one upper »binned pixel« row);
5. cut junk rows for Phase PI (two upper »binned pixel«);
6. split into even and odd sub-frames;
7. for each two single raw images (phase 0 and pi) create a plane with 4 extensions;
8. create an output fits files with four images extension and one binary table extension with the computed mean values of the overscan bias level and its rms (8 cols).

Since the zimpol frame is square, splitting the two sub-frames yields to the 1:2 aspect ratio. The output product is two fits-cube files (camera-1 and camera-2) of the ZPL EXP format specified as follows:

- phase zero odd sub-frame image;
- phase zero even sub-frame image;

- phase PI odd sub-frame image;
- phase PI even sub-frame;
- table of mean overscan bias level values and its rms (8 cols):
  - [1-col, 2-col] ADU1 ZERO PHASE OVSC MEAN & ADU1 ZERO PHASE OVSC RMS
  - [3-col, 4-col] ADU2 ZERO PHASE OVSC MEAN & ADU2 ZERO PHASE OVSC RMS
  - [5-col, 6-col] ADU1 PI PHASE OVSC MEAN & ADU1 PI PHASE OVSC RMS
  - [7-col, 8-col] ADU2 PI PHASE OVSC MEAN & ADU2 PI PHASE OVSC RMS

These pre-processing products may be used in all subsequent polarimetric recipes.

### 3.4.2.1.6 Products:

| Name         | Type              | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|--------------|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ PREPROC | FITS[Im(4),Bt(1)] | The output product is two fits-cube files with 5 extensions (for camera-1 and camera-2) of the ZPL EXP format specified as follows: - phase zero odd sub-frame image; - phase zero even sub-frame image; - phase PI odd sub-frame image; - phase PI even sub-frame; table of mean overscan bias level values and its rms (8 cols): - ADU1 ZERO PHASE OVSC MEAN, ADU1 ZERO PHASE OVSC RMS, ADU2 ZERO PHASE OVSC MEAN, ADU2 ZERO PHASE OVSC RMS, - ADU1 PI PHASE OVSC MEAN, ADU1 PI PHASE OVSC RMS, ADU2 PI PHASE OVSC MEAN, ADU2 PI PHASE OVSC RMS |

### 3.4.2.2 sph\_zpl\_master\_bias

#### 3.4.2.2.1 Purpose:

Create master bias, polarization modes.

#### 3.4.2.2.2 Input frames:

| Data Type (TAG)          | Source      | Optional | Min | Max |
|--------------------------|-------------|----------|-----|-----|
| ZPL_ BIAS_ RAW           | Raw data    | Yes      | 0   | Any |
| ZPL_ BIAS_ PREPROC       | Calibration | Yes      | 0   | Any |
| ZPL_ BIAS_ PREPROC_ CAM1 | Calibration | Yes      | 0   | Any |
| ZPL_ BIAS_ PREPROC_ CAM2 | Calibration | Yes      | 0   | Any |

### 3.4.2.2.3 Raw frame keywords used:

| Keyword              | Type   | Optional | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|----------------------|--------|----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ESO DRS PC PROD TYPE | string | No       | This keyword is mandatory if the pre-processed data are used. As the format of the zimpol pre-processed data is complicated, this keyword was introduced in order to guarantee that the pre-processed input frames are polarimetric pre-processed data, produced by the sph_zpl_preproc utility recipe. The value of this keyword is set up to >>SPH PC PREPROC ZPL EXP<<. Note: if raw data are used (default), then all keywords needed for the pre-processing recipe (see sph_zpl_preproc) must be presented in the raw data. |

### 3.4.2.2.4 Parameters:

| Name                                                    | Type   | Description                                                                                                                                                                 | Default                       | Allowed vals. |
|---------------------------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|---------------|
| zpl.master_<br>bias.outfilename                         | string | The output filename for the product of the camera-1/2. Please also see the esorex documentation for naming of output products.                                              | zpl_master_<br>bias.fits      | -             |
| zpl.master_<br>bias.outfilename_cam1                    | string | The output filename for the product of the camera-1. Please also see the esorex documentation for naming of output products.                                                | zpl_master_bias_<br>cam1.fits | -             |
| zpl.master_<br>bias.outfilename_cam2                    | string | The output filename for the product of the camera-2. Please also see the esorex documentation for naming of output products.                                                | zpl_master_bias_<br>cam2.fits | -             |
| zpl.master_<br>bias.subtract_overscan                   | bool   | Flag to set if the overscan mean values must be subtracted from pre-processed data (TRUE) Note that this parameter is applied if pre-processed data containt overscan table | 1                             | -             |
| zpl.master_bias.coll_<br>alg                            | int    | Set the collapse algorithm. The available algorithms: 0 = Mean, 1 = Median, 2 = Clean Mean. Default is 2 = Clean Mean                                                       | 2                             | 0,1,2         |
| zpl.master_bias.coll_<br>alg.clean_mean.reject_<br>high | int    | The number of pixels to reject when combining frames at the high end. Number of input frames must be > reject_high + reject_low                                             | 0                             | 0-20          |
| zpl.master_bias.coll_<br>alg.clean_mean.reject_<br>low  | int    | The number of pixels to reject when combining frames at the low end. Number of input frames must be > reject_high + reject_low                                              | 0                             | 0-20          |
| zpl.master_bias.clean_<br>mean.sigma                    | double | The number of pixels to reject when combining frames in sigma from median. NOT SUPPORTED YET!                                                                               | 5.0                           | 0.0-200.0     |

| Name                              | Type   | Description                                                                                                             | Default           | Allowed vals. |
|-----------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------|-------------------|---------------|
| zpl.master_<br>bias.sigma_clip    | double | The sigma clipping value for static badpixel detection. Default is 0 (no sigma clipping).                               | 0.0               | 0.0-200.0     |
| zpl.master_bias.keep_intermediate | bool   | Flag to set if intermediate data must be saved, namely pre-processed and overscan pre-processed subtracted data (FALSE) | 0                 | -             |
| zpl.preproc.outfilename_cam1      | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-1.                               | preproc_cam1.fits | -             |
| zpl.preproc.outfilename_cam2      | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-2.                               | preproc_cam2.fits | -             |

#### 3.4.2.2.5 Description:

This recipe creates a master bias calibration product for all polarization modes. The input frames might be either bias raw frames with the ZPL\_BIAS\_RAW tag or pre-processed bias frames, which should carry the ZPL\_BIAS\_PREPROC\_CAM1 and/or ZPL\_BIAS\_PREPROC\_CAM2 tags. No other frames are used in this recipe. If input frames are raw frames then the master bias recipe first performs the pre-processing step for all input frames (raw cubes), creating corresponding pre-processed frames (cubes) for both ZIMPOL cameras (see also sph\_zpl\_preproc for the detailed description of the pre-processing). The master bias for each camera is then created by combining pre-processed frames (= all planes) from the pre-processed cube(s) using a specified collapse algorithm (usually the clean\_mean algorithm, defined as a default one). If the flag >>subtract\_overscan<< is not set up to 0, then the recipe subtracts (before combining) the overscan bias level of the pre-processed cube(s) individually for each plane. Otherwise, the overscan subtraction step is skipped. (The calculated overscan bias levels – >>ADU1 mean overscan value<< from the left area of the image, and >>ADU2 mean overscan value<< from the right area of the image – for each phase (0 and pi) are saved anyway as a binary table in the pre-processed cube(s)). After all pre-processed frames (all 4 zpl exposure sub-frames) are combined in this way, the badpixel maps are determined on the result, using a simple sigma clipping algorithm. It sets the bad/hot pixels to be all those that are further than the >>specified sigma x the total RMS<< of the whole image away from the image median. The resulting master dark frames for both cameras are written out in the SPH QUAD (16 extensions) format specified as follows:

1. zpl exp phase zero odd sub-frame:

- master bias image,
- badpixel-map,
- ncomb-map,
- rms-map;

2. zpl exp phase zero even sub-frame:

- master bias image
- badpixel-map
- ncomb-map
- rms-map;

3. zpl exp phase PI odd sub-frame:

- master bias image,
- badpixel-map,
- ncomb-map,
- rms-map;

4. zpl exp phase PI even sub-frame:

- master bias image,
- badpixel-map,
- ncomb-map,
- rms-map.

Note that the default parameter for the sigma clipping `>>sigma_clip<<` is set up to 0. In this case the recipe will not detect `>>hot/bad pixels<<`, so all pixels will be considered as good ones in the product. Usually, the zpl exposure frames have the two vertical pixel stripes with strong `>>bias<<` signal. If the `>>sigma_clip<<` parameter is not 0, these pixels will be detected as bad ones and will be excluded from the subsequent treatment in the sphere pipeline (according to the sphere pipeline concept the detected bad pixel is marked as a bad in the badpixel-map and its rms value set to the 1e10 in the rms-map). Therefore, using the master bias for all subsequent polarimetric recipes in the default case (no sigma clipping), will preserve the signal in the vertical pixels stripes. The master polarimetric bias products may be used in the all subsequent polarimetric recipes.

### 3.4.2.2.6 Products:

| Name            | Type         | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|-----------------|--------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_MASTER_BIAS | FITS[Im(16)] | The resulting master bias frame is of the QUAD IMAGE format. This frame contains 16 image extensions (4 master frames), grouped by the following order: zpl exp phase zero odd sub-frame master bias image, badpixel-map, ncomb-map and rms-map; zpl exp phase zero even sub-frame master bias image, badpixel-map, ncomb-map and rms-map; zpl exp phase PI odd sub-frame master bias image, badpixel-map, ncomb-map and rms-map; zpl exp phase PI even sub-frame master bias image, badpixel-map, ncomb-map and rms-map. |



| Name                    | Type         | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|-------------------------|--------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ MASTER_ BIAS_ CAM1 | FITS[Im(16)] | The resulting master bias frame is of the QUAD IMAGE format. This frame contains 16 image extensions (4 master frames), grouped by the following order: zpl exp phase zero odd sub-frame master bias image, badpixel-map, ncomb-map and rms-map; zpl exp phase zero even sub-frame master bias image, badpixel-map, ncomb-map and rms-map; zpl exp phase PI odd sub-frame master bias image, badpixel-map, ncomb-map and rms-map; zpl exp phase PI even sub-frame master bias image, badpixel-map, ncomb-map and rms-map. |
| ZPL_ MASTER_ BIAS_ CAM2 | FITS[Im(16)] | The resulting master bias frame is of the QUAD IMAGE format. This frame contains 16 image extensions (4 master frames), grouped by the following order: zpl exp phase zero odd sub-frame master bias image, badpixel-map, ncomb-map and rms-map; zpl exp phase zero even sub-frame master bias image, badpixel-map, ncomb-map and rms-map; zpl exp phase PI odd sub-frame master bias image, badpixel-map, ncomb-map and rms-map; zpl exp phase PI even sub-frame master bias image, badpixel-map, ncomb-map and rms-map. |

3.4.2.3 sph\_zpl\_master\_dark

3.4.2.3.1 Purpose:

Create master dark, polarization modes.

3.4.2.3.2 Input frames:

| Data Type (TAG)          | Source      | Optional | Min | Max |
|--------------------------|-------------|----------|-----|-----|
| ZPL_ DARK_ RAW           | Raw data    | Yes      | 0   | Any |
| ZPL_ DARK_ PREPROC       | Calibration | Yes      | 0   | Any |
| ZPL_ DARK_ PREPROC_ CAM1 | Calibration | Yes      | 0   | Any |
| ZPL_ DARK_ PREPROC_ CAM2 | Calibration | Yes      | 0   | Any |
| ZPL_ MASTER_ BIAS        | Calibration | Yes      | 0   | 1   |
| ZPL_ MASTER_ BIAS_ CAM1  | Calibration | Yes      | 0   | 1   |
| ZPL_ MASTER_ BIAS_ CAM2  | Calibration | Yes      | 0   | 1   |

#### 3.4.2.3.3 Raw frame keywords used:

| Keyword              | Type   | Optional | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|----------------------|--------|----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ESO DRS PC PROD TYPE | string | No       | This keyword is mandatory if the pre-processed data are used. As the format of the zimpol pre-processed data is complicated, this keyword was introduced in order to guarantee that the pre-processed input frames are polarimetric pre-processed data, produced by the sph_zpl_preproc utility recipe. The value of this keyword is set up to >>SPH PC PREPROC ZPL EXP<<. Note: if raw data are used (default), then all keywords needed for the pre-processing recipe (see sph_zpl_preproc) must be presented in the raw data. |

#### 3.4.2.3.4 Parameters:

| Name                                                     | Type   | Description                                                                                                                                                                 | Default                       | Allowed vals. |
|----------------------------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|---------------|
| zpl.master_<br>dark.outfilename                          | string | The output filename for the product of the camera-1/2. Please also see the esorex documentation for naming of output products.                                              | zpl_master_<br>dark.fits      | -             |
| zpl.master_<br>dark.outfilename_cam1                     | string | The output filename for the product of the camera-1. Please also see the esorex documentation for naming of output products.                                                | zpl_master_<br>dark_cam1.fits | -             |
| zpl.master_<br>dark.outfilename_cam2                     | string | The output filename for the product of the camera-2. Please also see the esorex documentation for naming of output products.                                                | zpl_master_<br>dark_cam2.fits | -             |
| zpl.master_<br>dark.subtract_overscan                    | bool   | Flag to set if the overscan mean values must be subtracted from pre-processed data (TRUE) Note that this parameter is applied if pre-processed data containt overscan table | 1                             | -             |
| zpl.master_ dark.coll_<br>alg                            | int    | Set the collapse algorithm. The available algorithms: 0 = Mean, 1 = Median, 2 = Clean Mean. Default is 2 = Clean Mean                                                       | 2                             | 0,1,2         |
| zpl.master_ dark.coll_<br>alg.clean_mean.reject_<br>high | int    | The number of pixels to reject when combining frames at the high end. Number of input frames must be > reject_high +reject_low                                              | 0                             | 0-20          |
| zpl.master_ dark.coll_<br>alg.clean_mean.reject_<br>low  | int    | The number of pixels to reject when combining frames at the low end. Number of input frames must be > reject_high +reject_low                                               | 0                             | 0-20          |
| zpl.master_<br>dark.clean_mean.sigma                     | double | The number of pixels to reject when combining frames in sigma from median. NOT SUPPORTED YET!                                                                               | 5.0                           | 0.0-200.0     |
| zpl.master_<br>dark.sigma_clip                           | double | The sigma clipping value for static badpixel detection. Default is 0 (=inf).                                                                                                | 0.0                           | 0.0-200.0     |

| Name                                | Type   | Description                                                                                                             | Default            | Allowed vals. |
|-------------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------|--------------------|---------------|
| zpl.master_ dark.keep_ intermediate | bool   | Flag to set if intermediate data must be saved, namely pre-processed and overscan pre-processed subtracted data (FALSE) | 0                  | -             |
| zpl.preproc.outfilename_ cam1       | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-1.                               | preproc_ cam1.fits | -             |
| zpl.preproc.outfilename_ cam2       | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-2.                               | preproc_ cam2.fits | -             |

#### 3.4.2.3.5 Description:

This recipe creates the master dark calibration frame for the polarization mode. The input frames might be either dark raw frames with the ZPL\_DARK\_RAW tag or pre-processed dark frames, which should carry the ZPL\_DARK\_PREPROC\_CAM1 and/or ZPL\_DARK\_PREPROC\_CAM2 tags, and master bias frames (if any) with the ZPL\_MASTER\_BIAS\_CAM1 and/or ZPL\_MASTER\_BIAS\_CAM2 tags. If input frames are raw frames then the master dark recipe first performs the pre-processing step for all input frames (raw cubes), creating corresponding pre-processed frames (cubes) for both ZIMPOL cameras (see also sph\_zpl\_preproc for the detailed description of the pre-processing step). The master dark for each camera is then created by combining pre-processed frames (= all planes ) from the pre-processed cube(s) using a specified collapse algorithm (usually the clean\_mean algorithm, defined as a default one). If the flag `>>subtract_overscan<<` is not set up to 0, then the recipe subtracts (before combining) the overscan bias level of the pre-processed cube(s) individually for each plane. Otherwise, the overscan subtraction step is skipped. (The calculated overscan bias levels – `>>ADU1 mean overscan value<<` from the left area of the image, and `>>ADU2 mean overscan value<<` from the right area of the image – for each phase (0 and pi) are saved anyway as a binary table in the pre-processed cube(s)). After all pre-processed frames are combined in this way (all 4 zimpol exposure sub-frames), the badpixel maps are determined on the results, using a simple sigma clipping algorithm. It sets the bad/hot pixels to be all those that are further than the `>>specified sigma x the total RMS<<` of the whole image away from the image median. The resulting master dark frames are subtracted by master bias frames and the products of both cameras are written out in the QUAD IMAGE(16 extensions) format specified as follows:

1. zpl exp phase zero odd sub-frame:

- master dark image,
- badpixel-map,
- ncomb-map,
- rms-map;

2. zpl exp phase zero even sub-frame:

- master dark image
- badpixel-map
- ncomb-map
- rms-map;

3. zpl exp phase PI odd sub-frame:

- master dark image,

- badpixel-map,
- ncomb-map,
- rms-map;

4. zpl exp phase PI even sub-frame:

- master dark image,
- badpixel-map,
- ncomb-map,
- rms-map.

This master polarimetric dark products can be used in the all subsequent polarimetric recipes.

### 3.4.2.3.6 Products:

| Name                    | Type         | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|-------------------------|--------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ MASTER_ DARK       | FITS[Im(16)] | The resulting master dark frame is of the QUAD IMAGE format. This frame contains 16 image extensions (4 master frames), grouped by the following order: zpl exp phase zero odd sub-frame master dark image, badpixel-map, ncomb-map and rms-map; zpl exp phase zero even sub-frame master dark image, badpixel-map, ncomb-map and rms-map; zpl exp phase PI odd sub-frame master dark image, badpixel-map, ncomb-map and rms-map; zpl exp phase PI even sub-frame master dark image, badpixel-map, ncomb-map and rms-map. |
| ZPL_ MASTER_ DARK_ CAM1 | FITS[Im(16)] | The resulting master dark frame is of the QUAD IMAGE format. This frame contains 16 image extensions (4 master frames), grouped by the following order: zpl exp phase zero odd sub-frame master dark image, badpixel-map, ncomb-map and rms-map; zpl exp phase zero even sub-frame master dark image, badpixel-map, ncomb-map and rms-map; zpl exp phase PI odd sub-frame master dark image, badpixel-map, ncomb-map and rms-map; zpl exp phase PI even sub-frame master dark image, badpixel-map, ncomb-map and rms-map. |



| Name                 | Type         | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|----------------------|--------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_MASTER_DARK_CAM2 | FITS[Im(16)] | The resulting master dark frame is of the QUAD IMAGE format. This frame contains 16 image extensions (4 master frames), grouped by the following order: zpl exp phase zero odd sub-frame master dark image, badpixel-map, ncomb-map and rms-map; zpl exp phase zero even sub-frame master dark image, badpixel-map, ncomb-map and rms-map; zpl exp phase PI odd sub-frame master dark image, badpixel-map, ncomb-map and rms-map; zpl exp phase PI even sub-frame master dark image, badpixel-map, ncomb-map and rms-map. |

#### 3.4.2.4 sph\_zpl\_intensity\_flat

##### 3.4.2.4.1 Purpose:

Create intensity flat field, polarimetric modes.

##### 3.4.2.4.2 Input frames:

| Data Type (TAG)           | Source      | Optional | Min | Max |
|---------------------------|-------------|----------|-----|-----|
| ZPL_INT_FLAT_FIELD_RAW    | Raw data    | Yes      | 0   | Any |
| ZPL_INT_FLAT_PREPROC      | Calibration | Yes      | 0   | Any |
| ZPL_INT_FLAT_PREPROC_CAM1 | Calibration | Yes      | 0   | Any |
| ZPL_INT_FLAT_PREPROC_CAM2 | Calibration | Yes      | 0   | Any |
| ZPL_MASTER_BIAS           | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK           | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_CAM1      | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_CAM2      | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_CAM1      | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_CAM2      | Calibration | Yes      | 0   | 1   |
| ZPL_STATIC_BADPIXELMAP    | Calibration | Yes      | 0   | 1   |

##### 3.4.2.4.3 Raw frame keywords used:

| Keyword              | Type   | Optional | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|----------------------|--------|----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ESO DRS PC PROD TYPE | string | No       | This keyword is mandatory if the pre-processed data are used. As the format of the zimpol pre-processed data is complicated, this keyword was introduced in order to guarantee that the pre-processed input frames are polarimetric pre-processed data, produced by the sph_zpl_preproc utility recipe. Note: if raw data are used (default), then all keywords needed for the pre-processing recipe (see sph_zpl_preproc) must be presented in the raw data. |

##### 3.4.2.4.4 Parameters:

| Name                                       | Type   | Description                                                                                                                                                                                                   | Default                                       | Allowed vals. |
|--------------------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------|---------------|
| zpl.master_intensity_flat.outfilename      | string | The output filename of the final iff product for the camera-1/2. This product is usually used in all subsequent polarimetric recipes. Please also see the esorex documentation for naming of output products. | zpl_master_intensity_flat.fits                | -             |
| zpl.intensity_flat.outfilename             | string | The output filename for the quad image iff product for the camera-2. Please also see the esorex documentation for naming of output products.                                                                  | zpl_quad_intensity_flat.fits                  | -             |
| zpl.master_intensity_flat.outfilename_cam1 | string | The output filename of the final iff product for the camera-1/2. This product is usually used in all subsequent polarimetric recipes. Please also see the esorex documentation for naming of output products. | zpl_master_intensity_flat_cam1.fits           | -             |
| zpl.intensity_flat.outfilename_cam1        | string | The output filename of the quad image iff product of the camera-1. Please also see the esorex documentation for naming of output products.                                                                    | zpl_quad_intensity_flat_cam1.fits             | -             |
| zpl.master_intensity_flat.outfilename_cam2 | string | The output filename of the final iff product for the camera-2. This product is usually used in all subsequent polarimetric recipes. Please also see the esorex documentation for naming of output products.   | zpl_master_intensity_flat_cam2.fits           | -             |
| zpl.intensity_flat.outfilename_cam2        | string | The output filename for the quad image iff product for the camera-2. Please also see the esorex documentation for naming of output products.                                                                  | zpl_quad_intensity_flat_cam2.fits             | -             |
| zpl.intensity_flat.subtract_overscan       | bool   | Flag to set if the overscan mean values must be subtracted from pre-processed data (TRUE) Note that this parameter is applied if pre-processed data containt overscan table                                   | 1                                             | -             |
| zpl.intensity_flat.badpixfilename          | string | Controls the filename of the badpixel map, if requested for output. Ignored if make_badpix is FALSE.                                                                                                          | zpl_intensity_flat_nonlin_badpixels.fits      | -             |
| zpl.intensity_flat.badpixfilename_cam1     | string | Controls the filename of the badpixel map, if requested for output. Ignored if make_badpix is FALSE.                                                                                                          | zpl_intensity_flat_nonlin_badpixels_cam1.fits | -             |
| zpl.intensity_flat.badpixfilename_cam2     | string | Controls the filename of the badpixel map, if requested for output. Ignored if make_badpix is FALSE.                                                                                                          | zpl_intensity_flat_nonlin_badpixels_cam2.fits | -             |



| Name                                                               | Type   | Description                                                                                                                                                                                       | Default      | Allowed vals. |
|--------------------------------------------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|---------------|
| zpl.intensity_<br>flat.robust_fit                                  | bool   | Controls if fitting method is to be a robust linear fit. This will reduce the effect of cosmic rays and other temporary bad pixels. See e.g. Numerical Recipes for a description of the algorithm | 0            | -             |
| zpl.intensity_<br>flat.collapse                                    | bool   | Controls if the collapse is used to calculate intensity flat instead of the linear fitting                                                                                                        | 1            | -             |
| zpl.intensity_<br>flat.coll_<br>alg                                | int    | Set the collapse algorithm. The available algorithms: 0 = Mean, 1 = Median, 2 = Clean Mean. Default is 2 = Clean Mean                                                                             | 2            | 0,1,2         |
| zpl.intensity_<br>flat.coll_<br>alg.clean_<br>mean.reject_<br>high | int    | The number of pixels to reject when combining frames at the high end. Number of input frames must be > reject_high + reject_low                                                                   | 0            | 0-20          |
| zpl.intensity_<br>flat.coll_<br>alg.clean_<br>mean.reject_<br>low  | int    | The number of pixels to reject when combining frames at the low end. Number of input frames must be > reject_high + reject_low                                                                    | 0            | 0-20          |
| zpl.intensity_<br>flat.sigma_<br>clip                              | double | The sigma clipping value for static badpixel detection. Default is 5.                                                                                                                             | 5.0          | 0.0-200.0     |
| zpl.intensity_<br>flat.badpix_<br>lowtolerance                     | double | Threshold value for linearity badpixels. All pixels that have a flat field (slope) below this value will be flagged as bad.                                                                       | 0.1          | -             |
| zpl.intensity_<br>flat.badpix_<br>uptolerance                      | double | Threshold value for linearity badpixels. All pixels that have a flat field (slope) above this value will be flagged as bad.                                                                       | 10.0         | -             |
| zpl.intensity_<br>flat.badpix_<br>chisqtolerance                   | double | Threshold value for linearity badpixels. All pixels that have chi-squared value for the linear fit that is above this value will be flagged as bad.                                               | 50.0         | -             |
| zpl.intensity_<br>flat.quadimage_<br>weight_<br>mean               | bool   | Controls if the combining of the collapsed quad image to the final single master frame product is carried out using weighted mean or standard mean.                                               | 0            | -             |
| zpl.intensity_<br>flat.keep_<br>intermediate                       | bool   | Flag to set if intermediate data must be saved, namely pre-processed and overscan pre-processed subtracted data, linbadpix map and non-normalized products (FALSE)                                | 0            | -             |
| zpl.preproc.outfilename_<br>cam1                                   | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-1.                                                                                                         | preproc_cam1 | -             |
| zpl.preproc.outfilename_<br>cam2                                   | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-2.                                                                                                         | preproc_cam2 | -             |

#### 3.4.2.4.5 Description:

This recipe creates the master intensity flat field calibration frame for the polar-

ization modes. The input frames might be either intensity flat raw frames with the ZPL\_INT\_FLAT\_FIELD\_RAW tag or pre-processed intensity flat frames, which should carry the ZPL\_INT\_FLAT\_PREPROC\_CAM1 and/or ZPL\_INT\_FLAT\_PREPROC\_CAM2 tags, and master bias frames (if any) with the ZPL\_MASTER\_BIAS\_CAM1 and/or ZPL\_MASTER\_BIAS\_CAM2 tags, and master dark frames (if any) with the ZPL\_MASTER\_DARK\_CAM1 and/or ZPL\_MASTER\_DARK\_CAM2 tags. If input frames are raw frames then the intensity flat recipe first performs the pre-processing step for all input frames (raw cubes), creating corresponding pre-processed frames (cubes) for both ZIMPOL cameras (see also sph\_zpl\_preproc for the detailed description of the pre-processing step). The recipe creates for both cameras the intensity flat field calibration frame, using the input exposures which should be taken as described in the zimpol calibration plan. There are two main different methods to calculate the master intensity flatfield:

- combining frames (plus normalizing): in this case, the raw frames must be acquired with the same DIT and filter;
- linear fitting method of the individual pixels: in this case, the raw frames must be acquired either with a different DIT or with a different intensity of the lamp, but with the same filter.

The first <combining frames method> combines pre-processed raw intensity flatfield frame (= all planes) from the pre-processed cube(s) using the specified collapse algorithm (usually the clean\_mean algorithm, defined as a default one). After all pre-processed frames (all 4 zimpol exposure sub-frames) are combined in this way, the badpixel maps are determined on the results, using a simple sigma clipping algorithm. It sets the bad/hot pixels to be all those that are further than the >>specified sigma x the total RMS<< of the whole image away from the image median. Note that the badpixels which are stored in the master flat field product itself will contain all badpixels, accumulated at this point in the cascade (i.e. badpixels from the intensity flat and master dark, and master bias, if exists). The quad image intensity flat field products for both cameras are then written out in the fits files in the QUAD IMAGE format:

1. zpl exp phase zero odd sub-frame:

- intensity flat field image,
- badpixel-map,
- ncomb-map,
- rms-map;

2. zpl exp phase zero even sub-frame:

- intensity flat field image
- badpixel-map
- ncomb-map
- rms-map;

3. zpl exp phase PI odd sub-frame:

- intensity flat field image,
- badpixel-map,
- ncomb-map,
- rms-map;

4. zpl exp phase PI even sub-frame:

- intensity flat field image,

- badpixel-map,
- ncomb-map,
- rms-map.

Another products of the recipe are saved for both cameras in the MASTER FRAME format after combination of the resulting quad image into the final master frame products. This can be done either by simple averaging of the four sub-frames of the quad image or by using weighted mean formula where rms-map (calculated from error propagation) is taking into account to produce needed weights. These master intensity flat field calibration products (in the format of the MASTER FRAME) for both cameras are usually used in all subsequent polarimetric recipes that need to remove the pixel to pixel variation in the signal response of the detector. However, the quad image intensity flat field (in the format of the QUAD IMAGE, considered for monitoring purposes), may also feed the subsequent polarimetric recipes. The second <linear fitting flat fielding procedure> described below (identical to that for the IFS and IRDIS) is then applied to the each zpl exp polarimetric sub-frames ( zero odd, zero even, pi odd, pi even) seperately.

1. The mean value is determined for the respective sub-frame for all exposures.
2. For every pixel  $p = (x, y)$ , a set of  $m_i, v_i(x, y)$  data pairs are stored with  $m_i$  being the exposure mean value and  $v_i(x, y)$  being the pixel value for exposure  $i$ .
3. The flat field value is defined as the slope  $c_i$  of a linear fit F to the data  $m_i, v_i$ .
4. The fit itself is performed either using a maximum likelihood method or a robust fitting method which minimizes the sum of the absolute value of the deviations rather than the sum of the squares of the deviations (see e.g. Numerical Recipes for the algorithm). The robust fitting method will yield better results when significant outliers (e.g. due to cosmic rays) can be expected.
5. The flat field values (linear coefficients) are saved as an image as the main product of the recipe in the same QUAD IMAGE format (see above).

Additionally, the recipe may also produce a separate output of all pixels that are identified as non-linear. The criteria for non-linearity are set by the user parameters and can be either pixels that have a flat field value outside specified bounds and/or pixels for which the linear fit produces a reduced chi-squared above a given threshold value. For reliable non-linearity flagging using the reduced chi-squared it is necessary to use many high quality input exposures. Since the badpixel treatment is somewhat complicated, some important points: the badpixels that are stored in the master flat field itself as produced by this recipe contain all the badpixels (for each sub-frames individually) at this point in the cascade. Pixels that were marked as bad from the input static badpixel map are also marked as bad here. The optional static badpixel output that is produced contains strictly only those pixel that the flat field recipe itself deemed to be bad. This does not necessarily include all the badpixels from the static badpixel input file.

#### 3.4.2.4.6 Products:

| Name | Type | Description |
|------|------|-------------|
|------|------|-------------|



| Name                           | Type         | Description                                                                                                                                                                                                                                                                                                                                                                                                                  |
|--------------------------------|--------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_INT_FLAT_FIELD_MASTER      | FITS[Im(4)]  | The final master intensity flad field frame of the MASTER FRAME format which is used in all subsequent polarimetric recipes. This frame contains 4 image extensions: combined intensity flat image, badpixel-map, map of yhe combined number frames and rms.                                                                                                                                                                 |
| ZPL_INT_FLAT_FIELD             | FITS[Im(16)] | The resulting master intensity flad field frame of the QUAD IMAGE format. This frame contains 16 image extensions: intensity flat field zero odd image, badpixel-map, rms-map and weight-map; intensity flat field zero even image, badpixel-map, rms-map and weight-map; intensity flat field pi odd image, badpixel-map, rms-map and weight-map; intensity flat field pi even image, badpixel-map, rms-map and weight-map. |
| ZPL_INT_FLAT_FIELD_MASTER_CAM1 | FITS[Im(4)]  | The final master intensity flad field frame of the MASTER FRAME format which is used in all subsequent polarimetric recipes. This frame contains 4 image extensions: combined intensity flat image, badpixel-map, map of yhe combined number frames and rms.                                                                                                                                                                 |
| ZPL_INT_FLAT_FIELD_MASTER_CAM2 | FITS[Im(4)]  | The final master intensity flad field frame of the MASTER FRAME format which is used in in all subsequent polarimetric recipes. This frame contains 4 image extensions: combined intensity flat image, badpixel-map, map of yhe combined number frames and rms.                                                                                                                                                              |
| ZPL_INT_FLAT_FIELD_CAM1        | FITS[Im(16)] | The resulting master intensity flad field frame of the QUAD IMAGE format. This frame contains 16 image extensions: intensity flat field zero odd image, badpixel-map, rms-map and weight-map; intensity flat field zero even image, badpixel-map, rms-map and weight-map; intensity flat field pi odd image, badpixel-map, rms-map and weight-map; intensity flat field pi even image, badpixel-map, rms-map and weight-map. |

| Name                            | Type         | Description                                                                                                                                                                                                                                                                                                                                                                                                                  |
|---------------------------------|--------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_INT_FLAT_FIELD_CAM2         | FITS[Im(16)] | The resulting master intensity flat field frame of the QUAD IMAGE format. This frame contains 16 image extensions: intensity flat field zero odd image, badpixel-map, rms-map and weight-map; intensity flat field zero even image, badpixel-map, rms-map and weight-map; intensity flat field pi odd image, badpixel-map, rms-map and weight-map; intensity flat field pi even image, badpixel-map, rms-map and weight-map. |
| ZPL_NON_LINEAR_BADPIXELMAP      | FITS[Im(4)]  | Optional output of all the non-linear pixels determined. All pixels as determined in this recipe using the zpl.intensity_flat.badpix_low(up)tolerance parameters. phase zero odd sub-frame image; phase zero even sub-frame image; phase PI odd sub-frame image; phase PI even sub-frame.                                                                                                                                    |
| ZPL_NON_LINEAR_BADPIXELMAP_CAM1 | FITS[Im(4)]  | Optional output of all the non-linear pixels determined. All pixels as determined in this recipe using the zpl.intensity_flat.badpix_low(up)tolerance parameters. phase zero odd sub-frame image; phase zero even sub-frame image; phase PI odd sub-frame image; phase PI even sub-frame.                                                                                                                                    |
| ZPL_NON_LINEAR_BADPIXELMAP_CAM2 | FITS[Im(4)]  | Optional output of all the non-linear pixels determined. All pixels as determined in this recipe using the zpl.intensity_flat.badpix_low(up)tolerance parameters. phase zero odd sub-frame image; phase zero even sub-frame image; phase PI odd sub-frame image; phase PI even sub-frame.                                                                                                                                    |

### 3.4.2.5 sph\_zpl\_polarization\_flat

#### 3.4.2.5.1 Purpose:

Create polarization flat field, polarimetric modes.

#### 3.4.2.5.2 Input frames:

| Data Type (TAG)                | Source      | Optional | Min | Max |
|--------------------------------|-------------|----------|-----|-----|
| ZPL_POL_FLAT_FIELD_RAW         | Raw data    | Yes      | 0   | Any |
| ZPL_POL_FLAT_PREPROC           | Calibration | Yes      | 0   | Any |
| ZPL_POL_FLAT_PREPROC_CAM1      | Calibration | Yes      | 0   | Any |
| ZPL_POL_FLAT_PREPROC_CAM2      | Calibration | Yes      | 0   | Any |
| ZPL_MASTER_BIAS                | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_CAM1           | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_CAM2           | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK                | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_CAM1           | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_CAM2           | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD             | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_CAM1        | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_CAM2        | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_MASTER      | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_MASTER_CAM1 | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_MASTER_CAM2 | Calibration | Yes      | 0   | 1   |

#### 3.4.2.5.3 Raw frame keywords used:

| Keyword              | Type   | Optional | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|----------------------|--------|----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ESO DRS PC PROD TYPE | string | No       | This keyword is mandatory if the pre-processed data are used. As the format of the zimpol pre-processed data is complicated, this keyword was introduced in order to guarantee that the pre-processed input frames are polarimetric pre-processed data, produced by the sph_zpl_preproc utility recipe. Note: if raw data are used (default), then all keywords needed for the pre-processing recipe (see sph_zpl_preproc) must be presented in the raw data. |

#### 3.4.2.5.4 Parameters:

| Name                                   | Type   | Description                                                                                                                     | Default                         | Allowed vals. |
|----------------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------|
| zpl.polarization_flat.outfilename      | string | The output filename for the product for the camera-1/2. Please also see the esorex documentation for naming of output products. | zpl_polarization_flat.fits      | -             |
| zpl.polarization_flat.outfilename_cam1 | string | The output filename for the product for the camera-1. Please also see the esorex documentation for naming of output products.   | zpl_polarization_flat_cam1.fits | -             |
| zpl.polarization_flat.outfilename_cam2 | string | The output filename for the product for the camera-2. Please also see the esorex documentation for naming of output products.   | zpl_polarization_flat_cam2.fits | -             |

| Name                                                            | Type   | Description                                                                                                                                                                 | Default            | Allowed vals. |
|-----------------------------------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|---------------|
| zpl.polarization_<br>flat.subtract_ overscan                    | bool   | Flag to set if the overscan mean values must be subtracted from pre-processed data (TRUE) Note that this parameter is applied if pre-processed data containt overscan table | 1                  | -             |
| zpl.polarization_<br>flat.coll_ alg                             | int    | Set the collapse algorithm. The available algorithms: 0 = Mean, 1 = Median, 2 = Clean Mean. Default is 2 = Clean Mean                                                       | 2                  | 0,1,2         |
| zpl.polarization_<br>flat.coll_ alg.clean_<br>mean.reject_ high | int    | The number of pixels to reject when combining frames at the high end. Number of input frames must be > reject_high +reject_low                                              | 0                  | 0-20          |
| zpl.polarization_<br>flat.coll_ alg.clean_<br>mean.reject_ low  | int    | The number of pixels to reject when combining frames at the low end. Number of input frames must be > reject_high +reject_low                                               | 0                  | 0-20          |
| zpl.polarization_<br>flat.keep_ intermediate                    | bool   | Flag to set if intermediate date must be saved, namely pre-processed and overscan pre-processed subtracted data (FALSE)                                                     | 0                  | -             |
| zpl.preproc.outfilename_<br>cam1                                | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-1.                                                                                   | preproc_ cam1.fits | -             |
| zpl.preproc.outfilename_<br>cam2                                | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-2.                                                                                   | preproc_ cam2.fits | -             |

#### 3.4.2.5.5 Description:

This recipe creates the polarization flat field calibration frame for both cameras. The input frames might be either intesity flat raw frames with the ZPL\_POL\_FLAT\_FIELD\_RAW tag or pre-processed polarization flat-frames, which should carry the ZPL\_POL\_FLAT\_PREPROC\_CAM1 and/or tag ZPL\_POL\_FLAT\_PREPROC\_CAM2 tags, and master bias frames (if any) with the ZPL\_MASTER\_BIAS\_CAM1 and/or ZPL\_MASTER\_BIAS\_CAM2 tags, and master dark frames (if any) with the ZPL\_MASTER\_DARK\_CAM1 and/or ZPL\_MASTER\_DARK\_CAM2 tags, and master intensity flat field calibration frames with the ZPL\_INT\_FLAT\_FIELD\_MASTER\_CAM1 and/or ZPL\_INT\_FLAT\_FIELD\_MASTER\_CAM2 tags. The intensity flat calibration frames can be also used in the format of the QUAD IMAGE (see the description in sph\_zpl\_intensity\_flat recipe) with the corresponding ZPL\_INT\_FLAT\_FIELD\_CAM1 and/or ZPL\_INT\_FLAT\_FIELD\_CAM2 tags. If both formats of the intensity flat field calibrations are presented in sof-file the MASTER format will be used. If input frames are raw frames then the polarization flat recipe first performs the pre-processing step for all input frames (raw cubes), creating corresponding pre-processed frames (cubes) for both ZIMPOL cameras (see also sph\_zpl\_preproc for the detailed description of the pre-processing step). Then, all the pre-processed frames are read and combined using the specified collapse algorithm (usually the clean\_mean algorithm, defined as a default one) for each zpl exposure sub-frames. The combined frames for both cameras are of the QUAD IMAGE (16 extensions) format specified as follows: - zpl exp phase zero odd sub-frame combined image, badpixel-map, ncomb-map and rms-map; - zpl exp phase zero even sub-frame combined image, badpixel-map, ncomb-map and rms-map; - zpl

exp phase PI odd sub-frame master combined image, badpixel-map, ncomb-map and rms-map;  
- zpl exp phase PI even sub-frame master combined image, badpixel-map, ncomb-map and rms-map. The master bias, dark and intensity flat field are applied to this combined master frame and then the Stokes parameters (I,P) are calculated. The output master polarization flat field is written out in the DOUBLE IMAGE (8 images) format specified as follows: - master intensity Stokes parameter image, badpixel-map, ncomb-map and rms-map; - master polarization Stokes parameter image, badpixel-map, ncomb-map and rms-map. The master polarization flat field products for both cameras are used in all subsequent polarization recipes.

### 3.4.2.5.6 Products:

| Name                    | Type        | Description                                                                                                                                                                                                                                                                    |
|-------------------------|-------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_POL_FLAT_FIELD      | FITS[Im(8)] | The resulting polarization flat filed frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions grouped by the following order: master intensity image, badpixel-map, ncomb-map and rms-map; master polarization image, badpixel-map, ncomb-map and rms-map. |
| ZPL_POL_FLAT_FIELD_CAM1 | FITS[Im(8)] | The resulting polarization flat filed frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions grouped by the following order: master intensity image, badpixel-map, ncomb-map and rms-map; master polarization image, badpixel-map, ncomb-map and rms-map. |
| ZPL_POL_FLAT_FIELD_CAM2 | FITS[Im(8)] | The resulting polarization flat filed frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions grouped by the following order: intensity image, badpixel-map, ncomb-map and rms-map; polarization image, badpixel-map, ncomb-map and rms-map.               |

### 3.4.2.6 sph\_zpl\_modem\_efficiency

#### 3.4.2.6.1 Purpose:

Create modem efficiency, polarimetric modes.

#### 3.4.2.6.2 Input frames:

| Data Type (TAG)                     | Source      | Optional | Min | Max |
|-------------------------------------|-------------|----------|-----|-----|
| ZPL_ MODEM_ EFF_ RAW                | Raw data    | Yes      | 0   | Any |
| ZPL_ MODEM_ EFF_ PREPROC_ RAW       | Raw data    | Yes      | 0   | Any |
| ZPL_ MODEM_ EFF_ PREPROC_ CAM1      | Calibration | Yes      | 0   | Any |
| ZPL_ MODEM_ EFF_ PREPROC_ CAM2      | Calibration | Yes      | 0   | Any |
| ZPL_ MASTER_ BIAS                   | Calibration | Yes      | 0   | 1   |
| ZPL_ MASTER_ BIAS_ CAM1             | Calibration | Yes      | 0   | 1   |
| ZPL_ MASTER_ BIAS_ CAM2             | Calibration | Yes      | 0   | 1   |
| ZPL_ MASTER_ DARK                   | Calibration | Yes      | 0   | 1   |
| ZPL_ MASTER_ DARK_ CAM1             | Calibration | Yes      | 0   | 1   |
| ZPL_ MASTER_ DARK_ CAM2             | Calibration | Yes      | 0   | 1   |
| ZPL_ INT_ FLAT_ FIELD               | Calibration | Yes      | 0   | 1   |
| ZPL_ INT_ FLAT_ FIELD_ CAM1         | Calibration | Yes      | 0   | 1   |
| ZPL_ INT_ FLAT_ FIELD_ CAM2         | Calibration | Yes      | 0   | 1   |
| ZPL_ INT_ FLAT_ FIELD_ MASTER       | Calibration | Yes      | 0   | 1   |
| ZPL_ INT_ FLAT_ FIELD_ MASTER_ CAM1 | Calibration | Yes      | 0   | 1   |
| ZPL_ INT_ FLAT_ FIELD_ MASTER_ CAM2 | Calibration | Yes      | 0   | 1   |
| ZPL_ POL_ FLAT_ FIELD               | Calibration | Yes      | 0   | 1   |
| ZPL_ POL_ FLAT_ FIELD_ CAM1         | Calibration | Yes      | 0   | 1   |
| ZPL_ POL_ FLAT_ FIELD_ CAM2         | Calibration | Yes      | 0   | 1   |

#### 3.4.2.6.3 Raw frame keywords used:

| Keyword                    | Type   | Optional | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|----------------------------|--------|----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ESO DRS PC PROD TYPE       | string | No       | This keyword is mandatory if the pre-processed data are used. As the format of the zimpol pre-processed data is complicated, this keyword was introduced in order to guarantee that the pre-processed input frames are polarimetric pre-processed data, produced by the sph_zpl_preproc utility recipe. Note: if raw data are used (default), then all keywords needed for the pre-processing recipe (see sph_zpl_preproc) must be presented in the raw data. |
| ESO OCS3 ZIMPOL POL STOKES | string | No       | Stokes parameters (Qplus, Qminus)                                                                                                                                                                                                                                                                                                                                                                                                                             |

#### 3.4.2.6.4 Parameters:

| Name                                 | Type   | Description                                                                                                                                                                                                        | Default                        | Allowed vals. |
|--------------------------------------|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|---------------|
| zpl.modem_<br>efficiency.outfilename | string | The output filename of the final modem efficiency product for the camera-1/2. This product is used in all subsequent polarimetric recipes. Please also see the esorex documentation for naming of output products. | zpl_ modem_<br>efficiency.fits | -             |

| Name                                         | Type   | Description                                                                                                                                                                                                      | Default                              | Allowed vals. |
|----------------------------------------------|--------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------|---------------|
| zpl.modem_efficiency.outfilename_cam1        | string | The output filename of the final modem efficiency product for the camera-1. This product is used in all subsequent polarimetric recipes. Please also see the esorex documentation for naming of output products. | zpl_modem_efficiency_cam1.fits       | -             |
| zpl.modem_efficiency.outfilename_cam2        | string | The output filename of the final modem efficiency product for the camera-2. This product is used in all subsequent polarimetric recipes. Please also see the esorex documentation for naming of output products. | zpl_modem_efficiency_cam2.fits       | -             |
| zpl.modem_efficiency_qplus.outfilename       | string | The output filename of the qplus modem efficiency product for the camera-1/2. Please also see the esorex documentation for naming of output products.                                                            | zpl_modem_efficiency_plus.fits       | -             |
| zpl.modem_efficiency_qplus.outfilename_cam1  | string | The output filename of the qplus modem efficiency product for the camera-1. Please also see the esorex documentation for naming of output products.                                                              | zpl_modem_efficiency_plus_cam1.fits  | -             |
| zpl.modem_efficiency_qminus.outfilename      | string | The output filename of the qminus modem efficiency product for the camera-1/2. Please also see the esorex documentation for naming of output products.                                                           | zpl_modem_efficiency_minus.fits      | -             |
| zpl.modem_efficiency_qminus.outfilename_cam1 | string | The output filename of the qminus modem efficiency product for the camera-1. Please also see the esorex documentation for naming of output products.                                                             | zpl_modem_efficiency_minus_cam1.fits | -             |
| zpl.modem_efficiency_qplus.outfilename_cam2  | string | The output filename of the qplus modem efficiency product for the camera-2. Please also see the esorex documentation for naming of output products.                                                              | zpl_modem_efficiency_plus_cam2.fits  | -             |
| zpl.modem_efficiency_qminus.outfilename_cam2 | string | The output filename of the qminus modem efficiency product for the camera-2. Please also see the esorex documentation for naming of output products.                                                             | zpl_modem_efficiency_minus_cam2.fits | -             |
| zpl.modem_efficiency.subtract_overscan       | bool   | Flag to set if the overscan mean values must be subtracted from pre-processed data (TRUE) Note that this parameter is applied if pre-processed data containt overscan table                                      | 1                                    | -             |
| zpl.modem_efficiency.coll_alg                | int    | Set the collapse algorithm. The available algorithms: 0 = Mean, 1 = Median, 2 = Clean Mean. Default is 2 = Clean Mean                                                                                            | 2                                    | 0,1,2         |

| Name                                                 | Type   | Description                                                                                                                        | Default      | Allowed vals. |
|------------------------------------------------------|--------|------------------------------------------------------------------------------------------------------------------------------------|--------------|---------------|
| zpl.modem_efficiency.coll_alg.clean_mean.reject_high | int    | The number of pixels to reject when combining frames at the high end.<br>Number of input frames must be > reject_high + reject_low | 0            | 0-20          |
| zpl.modem_efficiency.coll_alg.clean_mean.reject_low  | int    | The number of pixels to reject when combining frames at the low end.<br>Number of input frames must be > reject_high + reject_low  | 0            | 0-20          |
| zpl.modem_efficiency.keep_intermediate               | bool   | Flag to set if intermediate data must be saved, namely pre-processed and overscan pre-processed subtracted data (FALSE)            | 0            | -             |
| zpl.preproc.outfilename_cam1                         | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-1.                                          | preproc_cam1 | -             |
| zpl.preproc.outfilename_cam2                         | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-2.                                          | preproc_cam2 | -             |

#### 3.4.2.6.5 Description:

The recipe creates master modulation/demodulation(modem) efficiency calibration product, using the input exposures which should be taken as described in the calibration plan. The input frames might be either modem efficiency raw frames with the ZPL\_MODEM\_EFF\_RAW tag, or pre-processed modem efficiency frames, which should carry the ZPL\_MODEM\_EFF\_PREPROC\_CAM1 and/or ZPL\_MODEM\_EFF\_PREPROC\_CAM2 tags, and master bias calibration frames (if any) with the ZPL\_MASTER\_BIAS\_CAM1 and/or ZPL\_MASTER\_BIAS\_CAM2 tags, and master dark calibration frames (if any) with the ZPL\_MASTER\_DARK\_CAM1 and/or ZPL\_MASTER\_DARK\_CAM2 tags, and master intensity flat field calibration frames with the ZPL\_INT\_FLAT\_FIELD\_MASTER\_CAM1 and/or ZPL\_INT\_FLAT\_FIELD\_MASTER\_CAM2 tags, and polarization flat field calibration frames with the ZPL\_POL\_FLAT\_PREPROC\_CAM1 and/or ZPL\_POL\_FLAT\_PREPROC\_CAM2 tags. The intensity flat calibration frames can be also used in the format of the QUAD IMAGE (see the description in sph\_zpl\_intensity\_flat recipe) with the corresponding ZPL\_INT\_FLAT\_FIELD\_CAM1 and/or ZPL\_INT\_FLAT\_FIELD\_CAM2 tags. If both formats of the intensity flat field calibrations are presented in sof-file the MASTER format will be used. If input frames are raw frames then the recipe first performs the pre-processing step for all input frames (raw cubes), creating corresponding pre-processed frames (cubes) for both ZIMPOL cameras (see also sph\_zpl\_preproc for the detailed description of the pre-processing step). Then all pre-processed modem frames are organized in the two groups distinguished from each other by the opposite sign of the Stokes parameter [Qplus, Qminus]. The frames from each group are combined using the specified collapse algorithm (usually the clean\_mean algorithm, defined as a default one) for each zpl exposure sub-frames. The combined frame is of the QUAD IMAGE (16 extensions) format specified as follows: - zpl exp phase zero odd sub-frame combined image, badpixel-map, ncomb-map and rms-map; - zpl exp phase zero even sub-frame combined image, badpixel-map, ncomb-map and rms-map; - zpl exp phase PI odd sub-frame master combined image, badpixel-map, ncomb-map and rms-map; - zpl exp phase PI even sub-frame master combined image, badpixel-map, ncomb-map and rms-map. The master bias, dark and intensity flat field are applied to the two [Qplus, Qminus] combined master frames and then the Stokes parameters (I,P) are calculated for both frames and both cameras in the form of DOUBLE IMAGE: - master intensity Stokes parameter image, badpixel-map, ncomb-map and rms-map; -

master polarization Stokes parameter image, badpixel-map, ncomb-map and rms-map. Then, the polarization flat field is applied to the [Qplus, Qminus] Stokes parameters double image frames. This intermediate modem efficiency products for +Q and -Q are saved in the separate files (quality check). Finally, the two opposite polarization frames are combined by subtracting the MINUS polarization image frame from the PLUS one. The output modem polarization efficiency frames for both camera are calculated by dividing the polarization image by the intensity image (P/I). The final modem products are thus of the MASTER FRAME format specified as follows: modem efficiency image, badpixel-map, ncomb-map and rms-map. Note: if rawdata consist only of Qplus-data (or only Qminus-data) then the final products will be created directly from Qplus (or Qminus) double image (P/I). The final modem efficiency products for both cameras are used in all subsequent polarization recipes.

#### 3.4.2.6.6 Products:

| Name                         | Type        | Description                                                                                                                                                                                                                                                                   |
|------------------------------|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ MODEM_ EFF              | FITS[Im(4)] | The final modem efficiency frame is of the MASTER FRAME format. This frame contains 4 image extensions: modem efficiency image, badpixel-map, ncomb-map and rms-map.                                                                                                          |
| ZPL_ MODEM_ EFF_ CAM1        | FITS[Im(4)] | The final modem efficiency frame is of the MASTER FRAME format. This frame contains 4 image extensions: modem efficiency image, badpixel-map, ncomb-map and rms-map.                                                                                                          |
| ZPL_ MODEM_ EFF_ QPLUS       | FITS[Im(8)] | The resulting +Q modem efficiency frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions: modem efficiency qplus intensity image, badpixel-map, ncomb-map and rms-map. modem efficiency qplus polarization image, badpixel-map, ncomb-map and rms-map.   |
| ZPL_ MODEM_ EFF_ QPLUS_ CAM1 | FITS[Im(8)] | The resulting +Q modem efficiency frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions: modem efficiency qplus intensity image, badpixel-map, ncomb-map and rms-map. modem efficiency qplus polarization image, badpixel-map, ncomb-map and rms-map.   |
| ZPL_ MODEM_ EFF_ QMINUS      | FITS[Im(8)] | The resulting -Q modem efficiency frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions: modem efficiency qminus intensity image, badpixel-map, ncomb-map and rms-map. modem efficiency qminus polarization image, badpixel-map, ncomb-map and rms-map. |

| Name                          | Type        | Description                                                                                                                                                                                                                                                                   |
|-------------------------------|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ MODEM_ EFF_ QMINUS_ CAM1 | FITS[Im(8)] | The resulting -Q modem efficiency frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions: modem efficiency qminus intensity image, badpixel-map, ncomb-map and rms-map. modem efficiency qminus polarization image, badpixel-map, ncomb-map and rms-map. |
| ZPL_ MODEM_ EFF_ CAM2         | FITS[Im(4)] | The final modem efficiency frame is of the MASTER FRAME format. This frame contains 4 image extensions: modem efficiency image, badpixel-map, ncomb-map and rms-map.                                                                                                          |
| ZPL_ MODEM_ EFF_ QPLUS_ CAM2  | FITS[Im(8)] | The resulting +Q modem efficiency frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions: modem efficiency qplus intensity image, badpixel-map, ncomb-map and rms-map. modem efficiency qplus polarization image, badpixel-map, ncomb-map and rms-map.   |
| ZPL_ MODEM_ EFF_ QMINUS_ CAM2 | FITS[Im(8)] | The resulting -Q modem efficiency frame is of the DOUBLE IMAGE format. This frame contains 8 image extensions: modem efficiency qminus intensity image, badpixel-map, ncomb-map and rms-map. modem efficiency qminus polarization image, badpixel-map, ncomb-map and rms-map. |

### 3.4.2.7 sph\_zpl\_star\_center\_pol

#### 3.4.2.7.1 Purpose:

Determine the center of the star center frame, polarimetry modes.

### 3.4.2.7.2 Input frames:

| Data Type (TAG)                  | Source      | Optional | Min | Max |
|----------------------------------|-------------|----------|-----|-----|
| ZPL_STAR_CENTER_POL_RAW          | Raw data    | Yes      | 0   | Any |
| ZPL_STAR_CENTER_POL_PREPROC      | Calibration | Yes      | 0   | Any |
| ZPL_STAR_CENTER_POL_PREPROC_CAM1 | Calibration | Yes      | 0   | Any |
| ZPL_STAR_CENTER_POL_PREPROC_CAM2 | Calibration | Yes      | 0   | Any |
| ZPL_MASTER_BIAS                  | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_CAM1             | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_CAM2             | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK                  | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_CAM1             | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_CAM2             | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD               | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_CAM1          | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_CAM2          | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_MASTER        | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_MASTER_CAM1   | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_MASTER_CAM2   | Calibration | Yes      | 0   | 1   |
| ZPL_POL_FLAT_FIELD               | Calibration | Yes      | 0   | 1   |
| ZPL_POL_FLAT_FIELD_CAM1          | Calibration | Yes      | 0   | 1   |
| ZPL_POL_FLAT_FIELD_CAM2          | Calibration | Yes      | 0   | 1   |
| ZPL_MODEM_EFF                    | Calibration | Yes      | 0   | 1   |
| ZPL_MODEM_EFF_CAM1               | Calibration | Yes      | 0   | 1   |
| ZPL_MODEM_EFF_CAM2               | Calibration | Yes      | 0   | 1   |

### 3.4.2.7.3 Raw frame keywords used:

| Keyword              | Type   | Optional | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|----------------------|--------|----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ESO DRS PC PROD TYPE | string | No       | <p>This keyword is mandatory if the pre-processed data are used. As the format of the zimpol pre-processed data is complicated, this keyword was introduced in order to guarantee that the pre-processed input frames are polarimetric pre-processed data, produced by the sph_zpl_preproc utility recipe. Note: if raw data are used (default), then all keywords needed for the pre-processing recipe (see sph_zpl_preproc) must be presented in the raw data.</p> <p>SPH_COMMON_KEYWORD_DROT2_MODE string<br/> 0 0 0 De-rotator mode: ELEV(pupil stabilized),<br/> SKY(field stabilized)</p> |

### 3.4.2.7.4 Parameters:

| Name | Type | Description | Default | Allowed vals. |
|------|------|-------------|---------|---------------|
|------|------|-------------|---------|---------------|



| Name                              | Type   | Description                                                                                                                                                                                                                                                                                                   | Default                       | Allowed vals. |
|-----------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|---------------|
| zpl.star_center.outfilename       | string | The output filename for the star center product, camera-1/2. Please also see the esorex documentation for naming of output products.                                                                                                                                                                          | zpl_star_center_pol.fits      | -             |
| zpl.star_center_cam1.outfilename  | string | The output filename for the star center product, camera-1. Please also see the esorex documentation for naming of output products.                                                                                                                                                                            | zpl_star_center_pol_cam1.fits | -             |
| zpl.star_center_cam2.outfilename  | string | The output filename for the star center product, camera-2. Please also see the esorex documentation for naming of output products.                                                                                                                                                                            | zpl_star_center_pol_cam2.fits | -             |
| zpl.star_center.subtract_overscan | bool   | Flag to set if the overscan mean values must be subtracted from pre-processed data (TRUE) Note that this parameter is applied if pre-processed data containt overscan table                                                                                                                                   | 1                             | -             |
| zpl.star_center.keep_intermediate | bool   | Flag to set if intermediate date must be saved, namely pre-processed and overscan pre-processed subtracted data (FALSE)                                                                                                                                                                                       | 0                             | -             |
| zpl.star_center.save_interprod    | bool   | Flag to set if the field center table must be saved as intermediate product (FALSE) Note that this parameter must be only applied for the offline pipeline                                                                                                                                                    | 0                             | -             |
| zpl.star_center.coll_alg          | int    | Set the collapse algorithm. The available algorithms: 0 = Mean, 1 = Median. Default is 0 = Mean.                                                                                                                                                                                                              | 0                             | 0,1,2         |
| zpl.star_center.filter_radius     | double | Filter radius for frame combination. A non zero value leads to suppression of high frequencies in the fourier domain before frame combination. The value expresses the minimum unsuppressed frequency as fraction of total frequency domain radius (a value of 1 would suppress essentially all frequencies). | 0.0                           | 0.0-1.0       |
| zpl.star_center.sigma             | double | The sigma threshold to use for source detections                                                                                                                                                                                                                                                              | 10.0                          | -             |
| zpl.star_center.unsharp_window    | int    | Before finding centres an unsharp algorithm is used on the image. This specifies the window width for the mask in pixels.                                                                                                                                                                                     | 4                             | -             |
| zpl.preproc.outfilename_cam1      | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-1.                                                                                                                                                                                                                     | preproc_cam1.fits             | -             |
| zpl.preproc.outfilename_cam2      | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-2.                                                                                                                                                                                                                     | preproc_cam2.fits             | -             |

#### 3.4.2.7.5 Description:

The recipe produces combined frame of the star center calibration measurements in

the polarization modes. The input frames might be either science polarimetric raw frames with the ZPL\_STAR\_CENTER\_POL\_RAW tag, or pre-processed science raw frames, which should carry the ZPL\_STAR\_CENTER\_POL\_PREPROC\_CAM1 and/or ZPL\_STAR\_CENTER\_POL\_PREPROC\_CAM2 tags, and calibration frames: - master bias calibration frames (if any) with the ZPL\_MASTER\_BIAS\_CAM1 and/or ZPL\_MASTER\_BIAS\_CAM2 tags, and - master dark calibration frames (if any) with the ZPL\_MASTER\_DARK\_CAM1 and/or ZPL\_MASTER\_DARK\_CAM2 tags, and - master intensity flat field calibration frames with the ZPL\_INT\_FLAT\_FIELD\_MASTER\_CAM1 and/or ZPL\_INT\_FLAT\_FIELD\_MASTER\_CAM2 tags, and - polarization flat field calibration frames with the ZPL\_POL\_FLAT\_PREPROC\_CAM1 and/or ZPL\_POL\_FLAT\_PREPROC\_CAM2 tags, and - modem/de-modulation (modem) efficiency calibration frames with the ZPL\_MODEM\_EFF\_CAM1 and/or ZPL\_MODEM\_EFF\_CAM1 tags. The intensity flat calibration frames can be also used in the format of the QUAD IMAGE (see the description in sph\_zpl\_intensity\_flat recipe) with the corresponding ZPL\_INT\_FLAT\_FIELD\_CAM1 and/or ZPL\_INT\_FLAT\_FIELD\_CAM2 tags. If both formats of the intensity flat field calibrations are presented in sof-file the MASTER format will be used. If input frames are raw frames then the recipe first performs the pre-processing step for all input frames (raw cubes), creating corresponding pre-processed frames (cubes) for both ZIMPOL cameras (see also sph\_zpl\_preproc for the detailed description of the pre-processing step). The pre-processed frames are then calibrated by subtracting a corresponding master bias frame and a master dark frame, and dividing the results by a given intensity flat field frame. Then the Stokes parameters are calculated for each group creating double image (I,P) frames. The polarization flat and modem efficiency calibrations are applied to the created double image frames of the Stokes parameters. Then the calibrated frames are de-dithered (if needed) and saved as intermediate products (note: if the zpl.science\_p1.save\_interprod is set to TRUE, the recipe will also save the so called field center table which contains the the calculated center positions for each plane of the pre-processed fits cube(s)). All calibrated and de-dithered frames are avareged using collapse mean algorithm. The combined start center frames of the DOUBLE IMAGE (8 extensions) format specified as follows: - combined intensity image (I), its badpixel-map, ncomb-map and rms-map. - combined polarimetric image (P), its badpixel-map, ncomb-map and rms-map. The combined star center image is then analysed using an aperture detection algorithm: - The aperture detection algorithm detects all connected regions of at least 4 pixels size (area) that are the given sigma above the background. - The so detected waffle stars are then used to contruct a geometric centre of all stars found. This is then the frame centre. The recipe also works for the case that there is only one star (e.g. the coronagraph is out and no waffle stars are formed). The coordinates of the detected frame centers are added as the keywords in the header of the output double images for each camera: - DRS ZPL STAR CENTER IFRAME XCOORD; - DRS ZPL STAR CENTER IFRAME YCOORD; - DRS ZPL STAR CENTER PFRAME XCOORD; - DRS ZPL STAR CENTER PFRAME YCOORD. This star center calibrated products for each camera should be used in the science polarimetric recipes.

### 3.4.2.7.6 Products:

| Name | Type | Description |
|------|------|-------------|
|------|------|-------------|

| Name                     | Type        | Description                                                                                                                                                                                                                                                                                                                                                                                                    |
|--------------------------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_STAR_CENTER_POL      | FITS[Im(8)] | The final combined star center calibration frame [I, P] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - combined intensity image of the star center calibration measurement with corresponding badpixel-map, ncomb-map and rms-map; - combined polarization image of the star center calibration measurement with corresponding badpixel-map, ncomb-map and rms-map;                  |
| ZPL_STAR_CENTER_POL_CAM1 | FITS[Im(8)] | The final combined star center calibration frame [I, P] for the camera-1 is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - combined intensity image of the star center calibration measurement with corresponding badpixel-map, ncomb-map and rms-map; - combined polarization image of the star center calibration measurement with corresponding badpixel-map, ncomb-map and rms-map; |
| ZPL_STAR_CENTER_POL_CAM2 | FITS[Im(8)] | The final combined star center calibration frame [I, P] for the camera-2 is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - combined intensity image of the star center calibration measurement with corresponding badpixel-map, ncomb-map and rms-map; - combined polarization image of the star center calibration measurement with corresponding badpixel-map, ncomb-map and rms-map; |

### 3.4.2.8 sph\_zpl\_science\_p1

#### 3.4.2.8.1 Purpose:

Reduce science frames of the Q and/or U observations in the polarization P1 mode.

### 3.4.2.8.2 Input frames:

| Data Type (TAG)                     | Source      | Optional | Min | Max |
|-------------------------------------|-------------|----------|-----|-----|
| ZPL_ SCIENCE_ P1_ RAW               | Raw data    | Yes      | 0   | Any |
| ZPL_ SCIENCE_ P1_ PREPROC           | Calibration | Yes      | 0   | Any |
| ZPL_ SCIENCE_ P1_ PREPROC_ CAM1     | Calibration | Yes      | 0   | Any |
| ZPL_ SCIENCE_ P1_ PREPROC_ CAM2     | Calibration | Yes      | 0   | Any |
| ZPL_ MASTER_ BIAS                   | Calibration | Yes      | 0   | 1   |
| ZPL_ MASTER_ BIAS_ CAM1             | Calibration | Yes      | 0   | 1   |
| ZPL_ MASTER_ BIAS_ CAM2             | Calibration | Yes      | 0   | 1   |
| ZPL_ MASTER_ DARK                   | Calibration | Yes      | 0   | 1   |
| ZPL_ MASTER_ DARK_ CAM1             | Calibration | Yes      | 0   | 1   |
| ZPL_ MASTER_ DARK_ CAM2             | Calibration | Yes      | 0   | 1   |
| ZPL_ INT_ FLAT_ FIELD               | Calibration | Yes      | 0   | 1   |
| ZPL_ INT_ FLAT_ FIELD_ CAM1         | Calibration | Yes      | 0   | 1   |
| ZPL_ INT_ FLAT_ FIELD_ CAM2         | Calibration | Yes      | 0   | 1   |
| ZPL_ INT_ FLAT_ FIELD_ MASTER       | Calibration | Yes      | 0   | 1   |
| ZPL_ INT_ FLAT_ FIELD_ MASTER_ CAM1 | Calibration | Yes      | 0   | 1   |
| ZPL_ INT_ FLAT_ FIELD_ MASTER_ CAM2 | Calibration | Yes      | 0   | 1   |
| ZPL_ POL_ FLAT_ FIELD               | Calibration | Yes      | 0   | 1   |
| ZPL_ POL_ FLAT_ FIELD_ CAM1         | Calibration | Yes      | 0   | 1   |
| ZPL_ POL_ FLAT_ FIELD_ CAM2         | Calibration | Yes      | 0   | 1   |
| ZPL_ MODEM_ EFF                     | Calibration | Yes      | 0   | 1   |
| ZPL_ MODEM_ EFF_ CAM1               | Calibration | Yes      | 0   | 1   |
| ZPL_ MODEM_ EFF_ CAM2               | Calibration | Yes      | 0   | 1   |
| ZPL_ STAR_ CENTER_ POL_ CAM1        | Calibration | Yes      | 0   | 1   |
| ZPL_ STAR_ CENTER_ POL_ CAM2        | Calibration | Yes      | 0   | 1   |
| ZPL_ STAR_ CENTER_ POL              | Calibration | Yes      | 0   | 1   |
| ZPL_ FIELD_ CENTER_ TABLE           | Calibration | Yes      | 0   | Any |
| ZPL_ POLHIGH_ STAR_ TABLE           | Calibration | Yes      | 0   | 1   |
| ZPL_ FILTER_ TABLE                  | Calibration | Yes      | 0   | 1   |
| ZPL_ POL_ CORRECT_ TABLE            | Calibration | Yes      | 0   | 1   |

### 3.4.2.8.3 Raw frame keywords used:

| Keyword                    | Type   | Optional | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|----------------------------|--------|----------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ESO DRS PC PROD TYPE       | string | No       | This keyword is mandatory if the pre-processed data are used. As the format of the zimpol pre-processed data is complicated, this keyword was introduced in order to guarantee that the pre-processed input frames are polarimetric pre-processed data, produced by the sph_zpl_preproc utility recipe. Note: if raw data are used (default), then all keywords needed for the pre-processing recipe (see sph_zpl_preproc) must be presented in the raw data.                                                                                                               |
| ESO OCS3 ZIMPOL POL STOKES | string | No       | Stokes parameters (Qplus, Qminus, Uplus, Uminus)<br>SPH_COMMON_KEYWORD_CAM1_DITHERING_X<br>double 0 0 100.0 X-position of the arm1(camera-1) [pix]<br>SPH_COMMON_KEYWORD_CAM1_DITHERING_Y<br>double 0 0 100.0 Y-position of the arm1(camera-1) [pix]<br>SPH_COMMON_KEYWORD_CAM2_DITHERING_X<br>double 0 0 100.0 X-position of the arm2(camera-2) [pix]<br>SPH_COMMON_KEYWORD_CAM2_DITHERING_Y<br>double 0 0 100.0 Y-position of the arm2(camera-2) [pix]<br>SPH_COMMON_KEYWORD_DROT2_MODE string<br>0 0 0 De-rotator mode: ELEV(pupil stabilized),<br>SKY(field stabilized) |

### 3.4.2.8.4 Parameters:

| Name                                     | Type   | Description                                                                                                                   | Default                                 | Allowed vals. |
|------------------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------|---------------|
| zpl.science_<br>p1.outfilename_ q        | string | The output filename for the final science product Q. Please also see the esorex documentation for naming of output products.  | zpl_ science_ p1_<br>q.fits             | -             |
| zpl.science_ p1_ plus_<br>q.outfilename  | string | The output filename for the science plus product +Q. Please also see the esorex documentation for naming of output products.  | zpl_ science_ p1_<br>plus_ q.fits       | -             |
| zpl.science_ p1_<br>minus_ q.outfilename | string | The output filename for the science minus product -Q. Please also see the esorex documentation for naming of output products. | zpl_ science_ p1_<br>minus_ q.fits      | -             |
| zpl.science_<br>p1.outfilename_ u        | string | The output filename for the final science product U. Please also see the esorex documentation for naming of output products.  | zpl_ science_ p1_<br>u.fits             | -             |
| zpl.science_ p1_ plus_<br>u.outfilename  | string | The output filename for the science plus product +U. Please also see the esorex documentation for naming of output products.  | zpl_ science_ p1_<br>plus_ u_ cam1.fits | -             |
| zpl.science_ p1_<br>minus_ u.outfilename | string | The output filename for the science minus product -U. Please also see the esorex documentation for naming of output products. | zpl_ science_ p1_<br>minus_ u.fits      | -             |



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| Name                                            | Type   | Description                                                                                                                   | Default                                  | Allowed vals. |
|-------------------------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------------|------------------------------------------|---------------|
| zpl.science_<br>p1.outfilename_ q_<br>cam1      | string | The output filename for the final science product Q. Please also see the esorex documentation for naming of output products.  | zpl_science_p1_<br>q_cam1.fits           | -             |
| zpl.science_p1_plus_<br>q_cam1.outfilename      | string | The output filename for the science plus product +Q. Please also see the esorex documentation for naming of output products.  | zpl_science_p1_<br>plus_q_cam1.fits      | -             |
| zpl.science_p1_<br>minus_q_<br>cam1.outfilename | string | The output filename for the science minus product -Q. Please also see the esorex documentation for naming of output products. | zpl_science_p1_<br>minus_q_<br>cam1.fits | -             |
| zpl.science_<br>p1.outfilename_ u_<br>cam1      | string | The output filename for the final science product U. Please also see the esorex documentation for naming of output products.  | zpl_science_p1_<br>u_cam1.fits           | -             |
| zpl.science_p1_plus_<br>u_cam1.outfilename      | string | The output filename for the science plus product +U. Please also see the esorex documentation for naming of output products.  | zpl_science_p1_<br>plus_u_cam1.fits      | -             |
| zpl.science_p1_<br>minus_u_<br>cam1.outfilename | string | The output filename for the science minus product -U. Please also see the esorex documentation for naming of output products. | zpl_science_p1_<br>minus_u_<br>cam1.fits | -             |
| zpl.science_<br>p1.outfilename_ q_<br>cam2      | string | The output filename for the final science product Q. Please also see the esorex documentation for naming of output products.  | zpl_science_p1_<br>q_cam2.fits           | -             |
| zpl.science_p1_plus_<br>q_cam2.outfilename      | string | The output filename for the science plus product +Q. Please also see the esorex documentation for naming of output products.  | zpl_science_p1_<br>plus_q_cam2.fits      | -             |
| zpl.science_p1_<br>minus_q_<br>cam2.outfilename | string | The output filename for the science minus product -Q. Please also see the esorex documentation for naming of output products. | zpl_science_p1_<br>minus_q_<br>cam2.fits | -             |
| zpl.science_<br>p1.outfilename_ u_<br>cam2      | string | The output filename for the final science product U. Please also see the esorex documentation for naming of output products.  | zpl_science_p1_<br>u_cam2.fits           | -             |
| zpl.science_p1_plus_<br>u_cam2.outfilename      | string | The output filename for the science plus product +U. Please also see the esorex documentation for naming of output products.  | zpl_science_p1_<br>plus_u_cam2.fits      | -             |
| zpl.science_p1_<br>minus_u_<br>cam2.outfilename | string | The output filename for the science minus product -U. Please also see the esorex documentation for naming of output products. | zpl_science_p1_<br>minus_u_<br>cam2.fits | -             |



| Name                                     | Type   | Description                                                                                                                                                                                                                                                                                                   | Default            | Allowed vals. |
|------------------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|---------------|
| zpl.science_<br>p1.subtract_ overscan    | bool   | Flag to set if the overscan mean values must be subtracted from pre-processed data (TRUE) Note that this parameter is applied if pre-processed data contain overscan table                                                                                                                                    | 1                  | -             |
| zpl.science_ p1.keep_<br>intermediate    | bool   | Flag to set if intermediate data must be saved, namely pre-processed and overscan pre-processed subtracted data (FALSE) Note that this setting this parameter to TRUE will use a very large amount of disk space                                                                                              | 0                  | -             |
| zpl.science_ p1.save_<br>interprod       | bool   | Flag to set if the field center table, plus the final calibrated cube without rotation, must be saved as intermediate product (FALSE) Note that this parameter must be only applied for the offline pipeline                                                                                                  | 0                  | -             |
| zpl.science_ p1.coll_<br>alg             | int    | Set the collapse algorithm. The available algorithms: 0 = Mean, 1 = Median. Default is 0 = Mean.                                                                                                                                                                                                              | 0                  | 0,1,2         |
| zpl.science_ p1.filter_<br>radius        | double | Filter radius for frame combination. A non zero value leads to suppression of high frequencies in the fourier domain before frame combination. The value expresses the minimum unsuppressed frequency as fraction of total frequency domain radius (a value of 1 would suppress essentially all frequencies). | 0.0                | 0.0-1.0       |
| zpl.science_ p1.star_<br>center_ iframe  | bool   | Flag to set if only the center coordinates of the iframe from the star center calibration frame should be used as a center coordinates to de-rotate iframe and pframe (TRUE)                                                                                                                                  | 1                  | -             |
| zpl.science_ p1.center_<br>xoffset_ cam1 | double | X-offset from the center of the image for cam1                                                                                                                                                                                                                                                                | 0.0                | -512.0-512.0  |
| zpl.science_ p1.center_<br>yoffset_ cam1 | double | Y-offset from the center of the image for cam1                                                                                                                                                                                                                                                                | 0.0                | -512.0-512.0  |
| zpl.science_ p1.center_<br>xoffset_ cam2 | double | X-offset from the center of the image for cam2                                                                                                                                                                                                                                                                | 0.0                | -512.0-512.0  |
| zpl.science_ p1.center_<br>yoffset_ cam2 | double | Y-offset from the center of the image for cam2                                                                                                                                                                                                                                                                | 0.0                | -512.0-512.0  |
| zpl.preproc.outfilename_<br>cam1         | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-1.                                                                                                                                                                                                                     | preproc_ cam1.fits | -             |
| zpl.preproc.outfilename_<br>cam2         | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-2.                                                                                                                                                                                                                     | preproc_ cam2.fits | -             |

#### 3.4.2.8.5 Description:

The recipe produces combined science frame [and corresponding Mueller matrix elements (not implemented!)] of the Q and/or U measurements the in the polarization modes. The input frames

might be either science polarimetric raw frames with the ZPL\_SCIENCE\_P1\_RAW tag, or pre-processed science raw frames, which should carry the ZPL\_SCIENCE\_P1\_PREPROC\_CAM1 and/or ZPL\_SCIENCE\_P1\_PREPROC\_CAM2 tags, and calibration frames: - master bias calibration frames (if any) with the ZPL\_MASTER\_BIAS\_CAM1 and/or ZPL\_MASTER\_BIAS\_CAM2 tags, and - master dark calibration frames (if any) with the ZPL\_MASTER\_DARK\_CAM1 and/or ZPL\_MASTER\_DARK\_CAM2 tags, and - master intensity flat field calibration frames with the ZPL\_INT\_FLAT\_FIELD\_MASTER\_CAM1 and/or ZPL\_INT\_FLAT\_FIELD\_MASTER\_CAM2 tags, and - polarization flat field calibration frames with the ZPL\_POL\_FLAT\_PREPROC\_CAM1 and/or ZPL\_POL\_FLAT\_PREPROC\_CAM2 tags, and - modem/de-modulation (modem) efficiency calibration frames with the ZPL\_MODEM\_EFF\_CAM1 and/or ZPL\_MODEM\_EFF\_CAM1 tags. The intensity flat calibration frames can be also used in the format of the QUAD IMAGE (see the description in sph\_zpl\_intensity\_flat recipe) with the corresponding ZPL\_INT\_FLAT\_FIELD\_CAM1 and/or ZPL\_INT\_FLAT\_FIELD\_CAM2 tags. If both formats of the intensity flat field calibrations are presented in sof-file the MASTER format will be used. If input frames are raw frames then the recipe first performs the pre-processing step for all input frames (raw cubes), creating corresponding pre-processed frames (cubes) for both ZIMPOL cameras (see also sph\_zpl\_preproc for the detailed description of the pre-processing step). Then, all pre-processed raw science frames are organized in the measurement groups with regards to the Stokes parameters: Q [Qplus, Qminus] and/or U [Uplus, Uminus]. These input frames frames should carry the SPH\_ZPL\_TAG\_SCIENCE\_P1\_PREPROC\_RAW tag. The pre-processed frames of each group for both cameras are then calibrated by subtracting a corresponding master bias frame and a master dark frame, and dividing the results by a corresponding intensity flat field frame. Then the Stokes parameters are calculated for each group creating double image (I,P) frames. The polarization flat and modem efficiency calibrations are applied to the created double image frames of the Stokes parameters. The calibrated frames of each group are then de-dithered, de-rotated and saved as intermediate products (note: if the zpl.science\_p1.save\_interprod is set to TRUE, the recipe will also save the so called field center table which contains the the calculated center positions and parallactical angles (to be more specific: an angle to be used for the de-rotation) for each plane of the pre-processed fits cube(s)). Note: the calibration frames with SPH\_ZPL\_TAG\_STAR\_CENTER\_POL\_CALIB\_CAM1(CAM2) tags provide the center coordinates to rotate around. If these calibrations are not presented the center of the frames will be used (normally, xc=yc=512 pixel). All de-dithered and de-rotated frames are averaged using collapse mean algorithm (for each group Qplus, Qminus, Uplus, Uminus). The combined frames of each groups of the DOUBLE IMAGE (8 extensions) format specified as follows: - combined intensity image (I), its badpixel-map, ncomb-map and rms-map. - combined polarimetric image (P), its badpixel-map, ncomb-map and rms-map. At the final step the double image frames (Qplus and Qminus) as well as (Uplus and Uminus) are combined polarimetrically (Q:  $I = [I(+Q) + I(-Q)]/2$ ,  $P = [P(+Q) - P(-Q)]/2$ ; U:  $I = [I(+U) + I(-U)]/2$ ,  $P = [P(+U) - P(-U)]/2$  ) The output Q and/or U double images for both cameras are reduced pipeline data products.

### 3.4.2.8.6 Products:

| Name | Type | Description |
|------|------|-------------|
|------|------|-------------|

| Name                              | Type        | Description                                                                                                                                                                                                                                                                                                                                                                |
|-----------------------------------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ SCIENCE_ P1_ REDUCED_ Q      | FITS[Im(8)] | The final combined science frame [I_Q, P_Q] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the Q measurement I_Q corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the Q measurement P_Q , corresponding badpixel-map, ncomb-map and rms-map;                        |
| ZPL_ SCIENCE_ P1_ REDUCED_ QPLUS  | FITS[Im(8)] | The resulting combined science frame of [+I_Q, +P_Q] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science plus intensity image of the +Q measurement +I_Q, corresponding badpixel-map, ncomb-map and rms-map; - reduced science plus polarization image of the +Q measurement +P_Q, corresponding badpixel-map, ncomb-map and rms-map; |
| ZPL_ SCIENCE_ P1_ REDUCED_ QMINUS | FITS[Im(8)] | The resulting combined science frame [-I_Q, -P_Q] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the -Q measurement -I_Q, corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the -Q measurement -P_Q, corresponding badpixel-map, ncomb-map and rms-map;              |
| ZPL_ SCIENCE_ P1_ REDUCED_ U      | FITS[Im(8)] | The final combined science frame [I_U, P_U] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the U measurement I_U, corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the U measurement P_U, corresponding badpixel-map, ncomb-map and rms-map;                        |



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| Name                              | Type        | Description                                                                                                                                                                                                                                                                                                                                                                            |
|-----------------------------------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_SCIENCE_P1_REDUCED_UPLUS      | FITS[Im(8)] | The resulting combined science frame of $[+I_U, +P_U]$ is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science plus intensity image of the $+U$ measurement $+I_U$ , corresponding badpixel-map, ncomb-map and rms-map; - reduced science plus polarization image of the $+U$ measurement $+P_U$ , corresponding badpixel-map, ncomb-map and rms-map; |
| ZPL_SCIENCE_P1_REDUCED_UMINUS     | FITS[Im(8)] | The resulting combined science frame $[-I_U, -P_U]$ is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the $-U$ measurement $-I_U$ , corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the $-U$ measurement $-P_U$ , corresponding badpixel-map, ncomb-map and rms-map;              |
| ZPL_SCIENCE_P1_REDUCED_Q_CAM1     | FITS[Im(8)] | The final combined science frame $[I_Q, P_Q]$ is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the $Q$ measurement $I_Q$ corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the $Q$ measurement $P_Q$ , corresponding badpixel-map, ncomb-map and rms-map;                          |
| ZPL_SCIENCE_P1_REDUCED_QPLUS_CAM1 | FITS[Im(8)] | The resulting combined science frame of $[+I_Q, +P_Q]$ is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science plus intensity image of the $+Q$ measurement $+I_Q$ , corresponding badpixel-map, ncomb-map and rms-map; - reduced science plus polarization image of the $+Q$ measurement $+P_Q$ , corresponding badpixel-map, ncomb-map and rms-map; |

| Name                                    | Type        | Description                                                                                                                                                                                                                                                                                                                                                                |
|-----------------------------------------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ SCIENCE_ P1_ REDUCED_ QMINUS_ CAM1 | FITS[Im(8)] | The resulting combined science frame [-I_Q, -P_Q] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the -Q measurement -I_Q, corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the -Q measurement -P_Q, corresponding badpixel-map, ncomb-map and rms-map;              |
| ZPL_ SCIENCE_ P1_ REDUCED_ U_ CAM1      | FITS[Im(8)] | The final combined science frame [I_U, P_U] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the U measurement I_U, corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the U measurement P_U, corresponding badpixel-map, ncomb-map and rms-map;                        |
| ZPL_ SCIENCE_ P1_ REDUCED_ UPLUS_ CAM1  | FITS[Im(8)] | The resulting combined science frame of [+I_U, +P_U] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science plus intensity image of the +U measurement +I_U, corresponding badpixel-map, ncomb-map and rms-map; - reduced science plus polarization image of the +U measurement +P_U, corresponding badpixel-map, ncomb-map and rms-map; |
| ZPL_ SCIENCE_ P1_ REDUCED_ UMINUS_ CAM1 | FITS[Im(8)] | The resulting combined science frame [-I_U, -P_U] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the -U measurement -I_U, corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the -U measurement -P_U, corresponding badpixel-map, ncomb-map and rms-map;              |

| Name                                          | Type        | Description                                                                                                                                                                                                                                                                                                                                                                |
|-----------------------------------------------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ SCIENCE_ P1_<br>REDUCED_ Q_<br>CAM2      | FITS[Im(8)] | The final combined science frame [I_Q, P_Q] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the Q measurement I_Q corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the Q measurement P_Q , corresponding badpixel-map, ncomb-map and rms-map;                        |
| ZPL_ SCIENCE_ P1_<br>REDUCED_ QPLUS_<br>CAM2  | FITS[Im(8)] | The resulting combined science frame of [+I_Q, +P_Q] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science plus intensity image of the +Q measurement +I_Q, corresponding badpixel-map, ncomb-map and rms-map; - reduced science plus polarization image of the +Q measurement +P_Q, corresponding badpixel-map, ncomb-map and rms-map; |
| ZPL_ SCIENCE_ P1_<br>REDUCED_<br>QMINUS_ CAM2 | FITS[Im(8)] | The resulting combined science frame [-I_Q, -P_Q] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the -Q measurement -I_Q, corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the -Q measurement -P_Q, corresponding badpixel-map, ncomb-map and rms-map;              |
| ZPL_ SCIENCE_ P1_<br>REDUCED_ U_<br>CAM2      | FITS[Im(8)] | The final combined science frame [I_U, P_U] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the U measurement I_U, corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the U measurement P_U, corresponding badpixel-map, ncomb-map and rms-map;                        |

| Name                                    | Type        | Description                                                                                                                                                                                                                                                                                                                                                                |
|-----------------------------------------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ SCIENCE_ P1_ REDUCED_ UPLUS_ CAM2  | FITS[Im(8)] | The resulting combined science frame of [+I_U, +P_U] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science plus intensity image of the +U measurement +I_U, corresponding badpixel-map, ncomb-map and rms-map; - reduced science plus polarization image of the +U measurement +P_U, corresponding badpixel-map, ncomb-map and rms-map; |
| ZPL_ SCIENCE_ P1_ REDUCED_ UMINUS_ CAM2 | FITS[Im(8)] | The resulting combined science frame [-I_U, -P_U] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the -U measurement -I_U, corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the -U measurement -P_U, corresponding badpixel-map, ncomb-map and rms-map;              |

### 3.4.2.9 sph\_zpl\_science\_p23

#### 3.4.2.9.1 Purpose:

Reduce science frames of the Q and/or U observations for the polarization P2 and P3 modes.

#### 3.4.2.9.2 Input frames:

| Data Type (TAG)                | Source      | Optional | Min | Max |
|--------------------------------|-------------|----------|-----|-----|
| ZPL_SCIENCE_P23_RAW            | Raw data    | Yes      | 0   | Any |
| ZPL_SCIENCE_P23_PREPROC_CAM1   | Calibration | Yes      | 0   | Any |
| ZPL_SCIENCE_P23_PREPROC_CAM2   | Calibration | Yes      | 0   | Any |
| ZPL_SCIENCE_P23_PREPROC        | Calibration | Yes      | 0   | Any |
| ZPL_MASTER_BIAS_CAM1           | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_BIAS_CAM2           | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_CAM1           | Calibration | Yes      | 0   | 1   |
| ZPL_MASTER_DARK_CAM2           | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_CAM1        | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_CAM2        | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_MASTER_CAM1 | Calibration | Yes      | 0   | 1   |
| ZPL_INT_FLAT_FIELD_MASTER_CAM2 | Calibration | Yes      | 0   | 1   |
| ZPL_POL_FLAT_FIELD_CAM1        | Calibration | Yes      | 0   | 1   |
| ZPL_POL_FLAT_FIELD_CAM2        | Calibration | Yes      | 0   | 1   |
| ZPL_MODEM_EFF_CAM1             | Calibration | Yes      | 0   | 1   |
| ZPL_MODEM_EFF_CAM2             | Calibration | Yes      | 0   | 1   |
| ZPL_STAR_CENTER_POL_CAM1       | Calibration | Yes      | 0   | 1   |
| ZPL_STAR_CENTER_POL_CAM2       | Calibration | Yes      | 0   | 1   |
| ZPL_STAR_CENTER_POL            | Calibration | Yes      | 0   | 1   |
| ZPL_FIELD_CENTER_TABLE         | Calibration | Yes      | 0   | Any |

#### 3.4.2.9.3 Raw frame keywords used:

| Keyword                    | Type   | Optional | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|----------------------------|--------|----------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ESO DRS PC PROD TYPE       | string | No       | This keyword is mandatory if the pre-processed data are used. As the format of the zimpol pre-processed data is complicated, this keyword was introduced in order to guarantee that the pre-processed input frames are polarimetric pre-processed data, produced by the sph_zpl_preproc utility recipe. Note: if raw data are used (default), then all keywords needed for the pre-processing recipe (see sph_zpl_preproc) must be presented in the raw data.                                                                                                               |
| ESO OCS3 ZIMPOL POL STOKES | string | No       | Stokes parameters (Qplus, Qminus, Uplus, Uminus)<br>SPH_COMMON_KEYWORD_CAM1_DITHERING_X<br>double 0 0 100.0 X-position of the arm1(camera-1) [pix]<br>SPH_COMMON_KEYWORD_CAM1_DITHERING_Y<br>double 0 0 100.0 Y-position of the arm1(camera-1) [pix]<br>SPH_COMMON_KEYWORD_CAM2_DITHERING_X<br>double 0 0 100.0 X-position of the arm2(camera-2) [pix]<br>SPH_COMMON_KEYWORD_CAM2_DITHERING_Y<br>double 0 0 100.0 Y-position of the arm2(camera-2) [pix]<br>SPH_COMMON_KEYWORD_DROT2_MODE string<br>0 0 0 De-rotator mode: ELEV(pupil stabilized),<br>SKY(field stabilized) |

#### 3.4.2.9.4 Parameters:



| Name                                               | Type   | Description                                                                                                                   | Default                                      | Allowed vals. |
|----------------------------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------|---------------|
| zpl.science_<br>p23.outfilename_ q_<br>cam1        | string | The output filename for the final science product Q. Please also see the esorex documentation for naming of output products.  | zpl_ science_ p23_<br>q_ cam1.fits           | -             |
| zpl.science_ p23_<br>plus_ q_<br>cam1.outfilename  | string | The output filename for the science plus product +Q. Please also see the esorex documentation for naming of output products.  | zpl_ science_ p23_<br>plus_ q_ cam1.fits     | -             |
| zpl.science_ p23_<br>minus_ q_<br>cam1.outfilename | string | The output filename for the science minus product -Q. Please also see the esorex documentation for naming of output products. | zpl_ science_ p23_<br>minus_ q_<br>cam1.fits | -             |
| zpl.science_<br>p23.outfilename_ u_<br>cam1        | string | The output filename for the final science product U. Please also see the esorex documentation for naming of output products.  | zpl_ science_ p23_<br>u_ cam1.fits           | -             |
| zpl.science_ p23_<br>plus_ u_<br>cam1.outfilename  | string | The output filename for the science plus product +U. Please also see the esorex documentation for naming of output products.  | zpl_ science_ p23_<br>plus_ u_ cam1.fits     | -             |
| zpl.science_ p23_<br>minus_ u_<br>cam1.outfilename | string | The output filename for the science minus product -U. Please also see the esorex documentation for naming of output products. | zpl_ science_ p23_<br>minus_ u_<br>cam1.fits | -             |
| zpl.science_<br>p23.outfilename_ q_<br>cam2        | string | The output filename for the final science product Q. Please also see the esorex documentation for naming of output products.  | zpl_ science_ p23_<br>q_ cam2.fits           | -             |
| zpl.science_ p23_<br>plus_ q_<br>cam2.outfilename  | string | The output filename for the science plus product +Q. Please also see the esorex documentation for naming of output products.  | zpl_ science_ p23_<br>plus_ q_ cam2.fits     | -             |
| zpl.science_ p23_<br>minus_ q_<br>cam2.outfilename | string | The output filename for the science minus product -Q. Please also see the esorex documentation for naming of output products. | zpl_ science_ p23_<br>minus_ q_<br>cam2.fits | -             |
| zpl.science_<br>p23.outfilename_ u_<br>cam2        | string | The output filename for the final science product U. Please also see the esorex documentation for naming of output products.  | zpl_ science_ p23_<br>u_ cam2.fits           | -             |
| zpl.science_ p23_<br>plus_ u_<br>cam2.outfilename  | string | The output filename for the science plus product +U. Please also see the esorex documentation for naming of output products.  | zpl_ science_ p23_<br>plus_ u_ cam2.fits     | -             |
| zpl.science_ p23_<br>minus_ u_<br>cam2.outfilename | string | The output filename for the science minus product -U. Please also see the esorex documentation for naming of output products. | zpl_ science_ p23_<br>minus_ u_<br>cam2.fits | -             |



| Name                                         | Type   | Description                                                                                                                                                                                                                                                                                                   | Default            | Allowed vals. |
|----------------------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|---------------|
| zpl.science_<br>p23.subtract_ overscan       | bool   | Flag to set if the overscan mean values must be subtracted from pre-processed data (TRUE) Note that this parameter is applied if pre-processed data containt overscan table                                                                                                                                   | 1                  | -             |
| zpl.science_ p23.keep_<br>intermediate       | bool   | Flag to set if intermediate data must be saved, namely pre-processed and overscan pre-processed subtracted data (FALSE) Note that this setting this parameter to TRUE will use a very large amount of disk space                                                                                              | 0                  | -             |
| zpl.science_ p23.save_<br>interprod          | bool   | Flag to set if the field center table, plus the final calibrated cube without rotation, must be saved as intermediate product (FALSE) Note that this parameter must be only applied for the offline pipeline                                                                                                  | 0                  | -             |
| zpl.science_ p23.coll_<br>alg                | int    | Set the collapse algorithm. The available algorithms: 0 = Mean, 1 = Median. Default is 0 = Mean.                                                                                                                                                                                                              | 0                  | 0,1,2         |
| zpl.science_ p23.filter_<br>radius           | double | Filter radius for frame combination. A non zero value leads to suppression of high frequencies in the fourier domain before frame combination. The value expresses the minimum unsuppressed frequency as fraction of total frequency domain radius (a value of 1 would suppress essentially all frequencies). | 0.0                | 0.0-1.0       |
| zpl.science_ p23.star_<br>center_ iframe     | bool   | Flag to set if only the center coordinates of the iframe from the star center calibration frame should be used as a center coordinates to de-rotate iframe and pframe (TRUE)                                                                                                                                  | 1                  | -             |
| zpl.science_<br>p23.center_ xoffset_<br>cam1 | double | X-offset from the center of the image for cam1                                                                                                                                                                                                                                                                | 0.0                | -512.0-512.0  |
| zpl.science_<br>p23.center_ yoffset_<br>cam1 | double | Y-offset from the center of the image for cam1                                                                                                                                                                                                                                                                | 0.0                | -512.0-512.0  |
| zpl.science_<br>p23.center_ xoffset_<br>cam2 | double | X-offset from the center of the image for cam2                                                                                                                                                                                                                                                                | 0.0                | -512.0-512.0  |
| zpl.science_<br>p23.center_ yoffset_<br>cam2 | double | Y-offset from the center of the image for cam2                                                                                                                                                                                                                                                                | 0.0                | -512.0-512.0  |
| zpl.preproc.outfilename_<br>cam1             | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-1.                                                                                                                                                                                                                     | preproc_ cam1.fits | -             |
| zpl.preproc.outfilename_<br>cam2             | string | The postfix- of the intermediate filename of the pre-processed raw data for the CAMERA-2.                                                                                                                                                                                                                     | preproc_ cam2.fits | -             |

### 3.4.2.9.5 Description:

The recipe produces combined science frame [and corresponding Mueller matrix elements (not implemented)] of the Q and/or U measurements in the polarization modes. The input frames might be either science polarimetric raw frames with the ZPL\_SCIENCE\_P23\_RAW tag, or pre-processed science raw frames, which should carry the ZPL\_SCIENCE\_P23\_PREPROC\_CAM1 and/or ZPL\_SCIENCE\_P23\_PREPROC\_CAM2 tags, and calibration frames: - master bias calibration frames (if any) with the ZPL\_MASTER\_BIAS\_CAM1 and/or ZPL\_MASTER\_BIAS\_CAM2 tags, and - master dark calibration frames (if any) with the ZPL\_MASTER\_DARK\_CAM1 and/or ZPL\_MASTER\_DARK\_CAM2 tags, and - master intensity flat field calibration frames with the ZPL\_INT\_FLAT\_FIELD\_MASTER\_CAM1 and/or ZPL\_INT\_FLAT\_FIELD\_MASTER\_CAM2 tags, and - polarization flat field calibration frames with the ZPL\_POL\_FLAT\_PREPROC\_CAM1 and/or ZPL\_POL\_FLAT\_PREPROC\_CAM2 tags, and - modem/de-modulation (modem) efficiency calibration frames with the ZPL\_MODEM\_EFF\_CAM1 and/or ZPL\_MODEM\_EFF\_CAM2 tags. The intensity flat calibration frames can be also used in the format of the QUAD IMAGE (see the description in sph\_zpl\_intensity\_flat recipe) with the corresponding ZPL\_INT\_FLAT\_FIELD\_CAM1 and/or ZPL\_INT\_FLAT\_FIELD\_CAM2 tags. If both formats of the intensity flat field calibrations are presented in sof-file the MASTER format will be used. If input frames are raw frames then the polarization flat recipe first performs the pre-processing step for all input frames (raw cubes), creating corresponding pre-processed frames (cubes) for both ZIMPOL cameras (see also sph\_zpl\_preproc for the detailed description of the pre-processing step). Then, all pre-processed raw science frames are organized in the measurement groups with regards to the Stokes parameters: Q [Qplus, Qminus] and/or U [Uplus, Uminus]. These input frames should carry the SPH\_ZPL\_TAG\_SCIENCE\_P23\_PREPROC\_RAW tag. The pre-processed frames of each group for both cameras are then calibrated by subtracting a corresponding master bias frame and a master dark frame, and dividing the results by a corresponding intensity flat field frame. Then the Stokes parameters are calculated for each group creating double image (I,P) frames. The polarization flat and modem efficiency calibrations are applied to the created double image frames of the Stokes parameters. The calibrated frames of each group are then de-dithered, de-rotated and saved as intermediate products (note: if the zpl.science\_p23.save\_interprod is set to the 1, the recipe will also save the so called field center table which contains the calculated center positions for each plane of the pre-processed fits cube(s)). All de-dithered frames are averaged using collapse mean algorithm (for each group Qplus, Qminus, Uplus, Uminus). The combined frames of each groups of the DOUBLE IMAGE (8 extensions) format specified as follows: - combined intensity image (I), its badpixel-map, ncomb-map and rms-map. - combined polarimetric image (P), its badpixel-map, ncomb-map and rms-map. At the final step the double image frames (Qplus and Qminus) as well as (Uplus and Uminus) are combined polarimetrically (Q:  $I = [I(+Q) + I(-Q)]/2$ ,  $P = [P(+Q) - P(-Q)]/2$ ; U:  $I = [I(+U) + I(-U)]/2$ ,  $P = [P(+U) - P(-U)]/2$ ) The output Q and/or U double images for both cameras are reduced pipeline data products.

### 3.4.2.9.6 Products:

| Name | Type | Description |
|------|------|-------------|
|------|------|-------------|

| Name                                           | Type        | Description                                                                                                                                                                                                                                                                                                                                                                |
|------------------------------------------------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ SCIENCE_<br>P23_ REDUCED_ Q_<br>CAM1      | FITS[Im(8)] | The final combined science frame [I_Q, P_Q] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the Q measurement I_Q corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the Q measurement P_Q , corresponding badpixel-map, ncomb-map and rms-map;                        |
| ZPL_ SCIENCE_<br>P23_ REDUCED_<br>QPLUS_ CAM1  | FITS[Im(8)] | The resulting combined science frame of [+I_Q, +P_Q] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science plus intensity image of the +Q measurement +I_Q, corresponding badpixel-map, ncomb-map and rms-map; - reduced science plus polarization image of the +Q measurement +P_Q, corresponding badpixel-map, ncomb-map and rms-map; |
| ZPL_ SCIENCE_<br>P23_ REDUCED_<br>QMINUS_ CAM1 | FITS[Im(8)] | The resulting combined science frame [-I_Q, -P_Q] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the -Q measurement -I_Q, corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the -Q measurement -P_Q, corresponding badpixel-map, ncomb-map and rms-map;              |
| ZPL_ SCIENCE_<br>P23_ REDUCED_ U_<br>CAM1      | FITS[Im(8)] | The resulting combined science frame [I_U, P_U] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the U measurement I_U, corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the U measurement P_U, corresponding badpixel-map, ncomb-map and rms-map;                    |

| Name                                           | Type        | Description                                                                                                                                                                                                                                                                                                                                                                |
|------------------------------------------------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ SCIENCE_<br>P23_ REDUCED_<br>UPLUS_ CAM1  | FITS[Im(8)] | The resulting combined science frame of [+I_U, +P_U] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science plus intensity image of the +U measurement +I_U, corresponding badpixel-map, ncomb-map and rms-map; - reduced science plus polarization image of the +U measurement +P_U, corresponding badpixel-map, ncomb-map and rms-map; |
| ZPL_ SCIENCE_<br>P23_ REDUCED_<br>UMINUS_ CAM1 | FITS[Im(8)] | The resulting combined science frame [-I_U, -P_U] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the -U measurement -I_U, corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the -U measurement -P_U, corresponding badpixel-map, ncomb-map and rms-map;              |
| ZPL_ SCIENCE_<br>P23_ REDUCED_ Q_<br>CAM2      | FITS[Im(8)] | The resulting combined science frame [I_Q, P_Q] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the Q measurement I_Q corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the Q measurement P_Q, corresponding badpixel-map, ncomb-map and rms-map;                     |
| ZPL_ SCIENCE_<br>P23_ REDUCED_<br>QPLUS_ CAM2  | FITS[Im(8)] | The resulting combined science frame of [+I_Q, +P_Q] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science plus intensity image of the +Q measurement +I_Q, corresponding badpixel-map, ncomb-map and rms-map; - reduced science plus polarization image of the +Q measurement +P_Q, corresponding badpixel-map, ncomb-map and rms-map; |

| Name                                           | Type        | Description                                                                                                                                                                                                                                                                                                                                                                |
|------------------------------------------------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ZPL_ SCIENCE_<br>P23_ REDUCED_<br>QMINUS_ CAM2 | FITS[Im(8)] | The resulting combined science frame [-I_Q, -P_Q] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the -Q measurement -I_Q, corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the -Q measurement -P_Q, corresponding badpixel-map, ncomb-map and rms-map;              |
| ZPL_ SCIENCE_<br>P23_ REDUCED_ U_<br>CAM2      | FITS[Im(8)] | The resulting combined science frame [I_U, P_U] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the U measurement I_U, corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the U measurement P_U, corresponding badpixel-map, ncomb-map and rms-map;                    |
| ZPL_ SCIENCE_<br>P23_ REDUCED_<br>UPLUS_ CAM2  | FITS[Im(8)] | The resulting combined science frame of [+I_U, +P_U] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science plus intensity image of the +U measurement +I_U, corresponding badpixel-map, ncomb-map and rms-map; - reduced science plus polarization image of the +U measurement +P_U, corresponding badpixel-map, ncomb-map and rms-map; |
| ZPL_ SCIENCE_<br>P23_ REDUCED_<br>UMINUS_ CAM2 | FITS[Im(8)] | The resulting combined science frame [-I_U, -P_U] is of the DOUBLE IMAGE format. This frame contains 8 image extensions: - reduced science intensity image of the -U measurement -I_U, corresponding badpixel-map, ncomb-map and rms-map; - reduced science polarization image of the -U measurement -P_U, corresponding badpixel-map, ncomb-map and rms-map;              |

### 3.4.3 ZIMPOL Workflow Summary

The ZIMPOL imaging workflow is summarized in Fig.3.6, the polarimetric workflow in Fig.3.7.

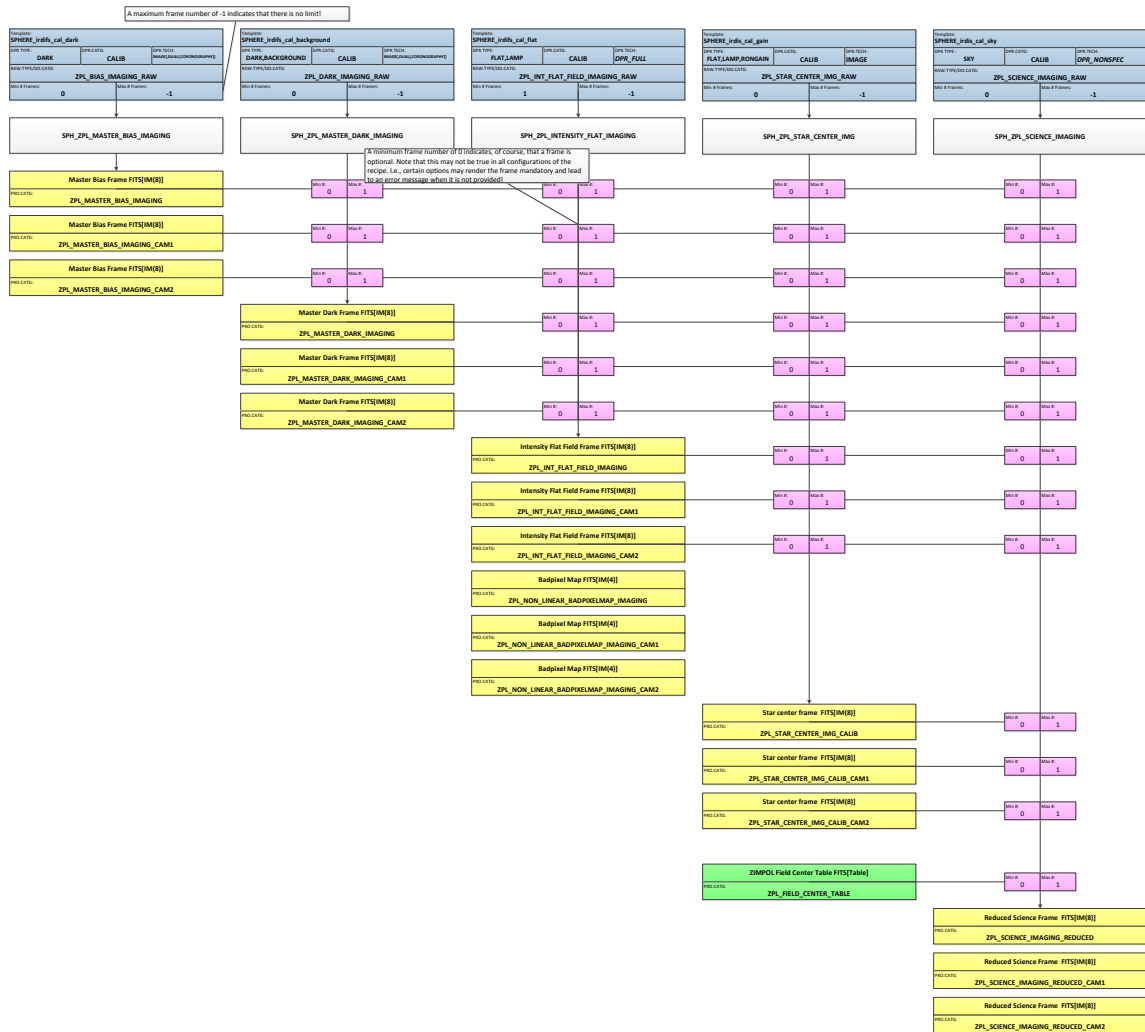


Figure 3.6: ZIMPOL Imaging Workflow

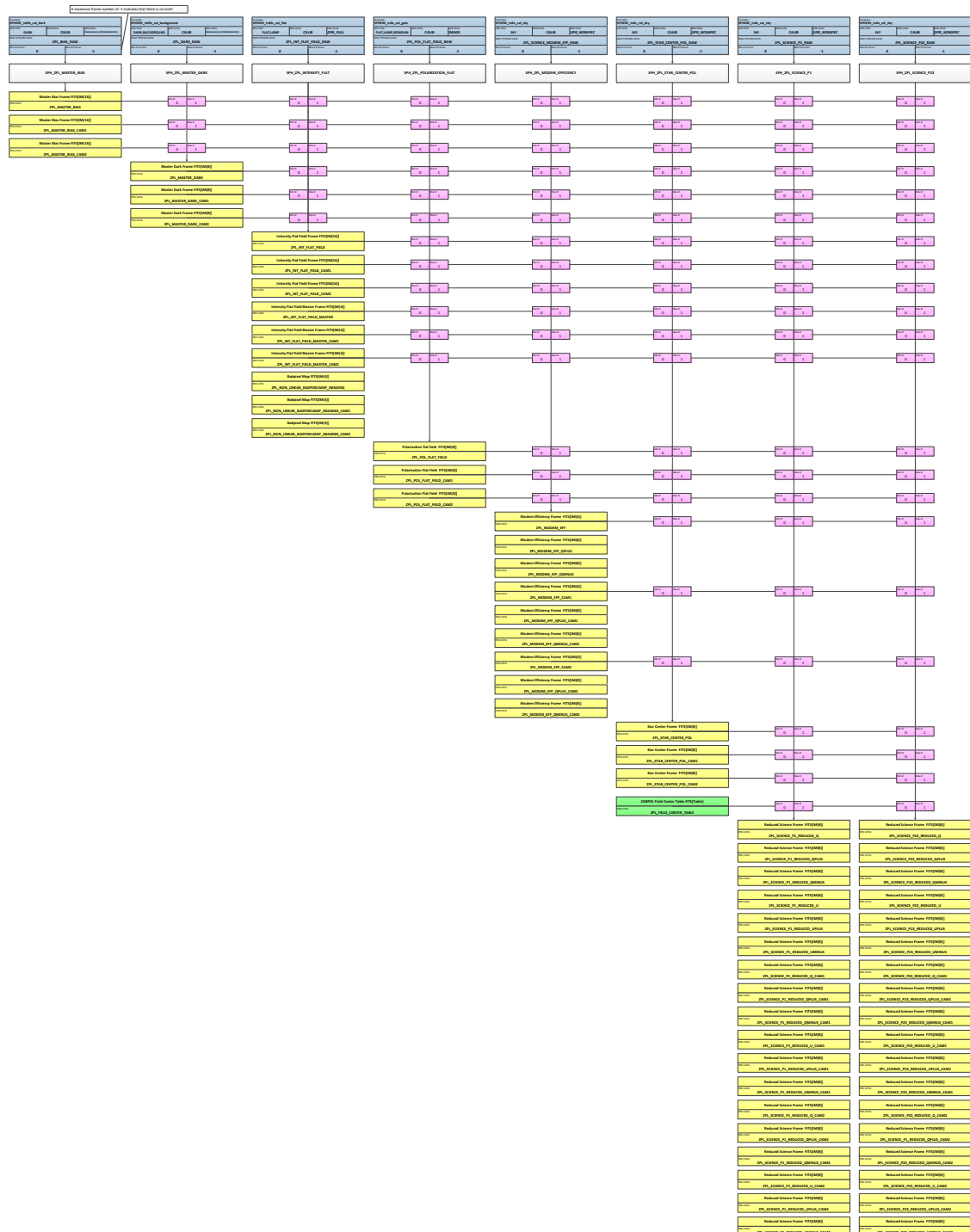


Figure 3.7: ZIMPOL Polarimetry Workflow

## Chapter 4

# Instrument Data Description

In this section we describe the raw data, including the for DRH relevant DPR keywords for each data type. All valid combinations of FITS DPR keywords are identified, listed and identified with corresponding recipes which need to use them as input.

For each of these data structures the basic data type is a FITS file with an image in the HDU corresponding to the full 2048x2048 pixel region of the detector and no extensions. The keywords in the header of the FITS file depend strongly on the data structure represented. The following table lists the keywords for each of the data structures for technical, science and monitoring calibrations.

**General Data Layout** A raw SPHERE file always has the images stored in the primary FITS data unit. Please see the FDR document for a table that lists the raw data types, the corresponding calibrations (names as in the calibration plan) etc. In sections 9-11 of this manual the data types, keywords etc are listed for each recipe.

**Imaging Frames** The raw imaging frames for IFS and IRDIS all contain in total 2048x2048 pixels. For IRDIS all raw frames that are obtained with calibrations that illuminate the detector through the IRDIS optical path, only an area of 2048x1024 pixels is used. This again is split in two parts for classical imaging and DBI modes.

**Image Coordinate System** In several places the SPHERE recipes report coordinates, in particular of a reported frame center, determined star position, or similar. These positions are communicated to the user by the means of header keywords or dedicated product files, either as FITS tables or, optionally, simply ASCII output. When comparing these coordinates to values derived by the means of using other tools, care should be taken about the coordinate system in use. Many ways exist to describe locations in image frames, and while the SPHERE pipeline uses pixel coordinates, there are also different ways of defining the pixel grid coordinate system. The FITS standard has its own definition, and the various FITS viewing tools and scripting (and other programming) languages follow different standards.

Coordinates reported (or used as input) by the SPHERE pipeline always refer to the following scheme: For an image consisting of  $N \times M$  pixels, the coordinate (0,0) refers to the lower left corner of the lower left pixel. The coordinate (N,M) refers to the upper right corner of the upper right pixel. The midpoint of the lower left pixel has the coordinate (0.5,0.5), and the image midpoint (N/2,M/2).



## 4.1 ZIMPOL Data

### 4.1.1 Header Keywords Used by ZIMPOL Recipes

"ESO DET CHIP INDEX"  
"ESO ZPL STOCK PARAMETER SIGN"  
"ESO ZPL STOCK PARAMETER\_NAME"  
"ESO OCS3 ZIMPOL POL STOKES"  
"ESO DET READ CURNAME"  
"ESO DET OUT1 X"  
"ESO DET OUT1 Y"  
"ESO DET BINX" Binning  
"ESO DET BINY" Binning  
"ESO DET OUT1 NX"  
"ESO DET OUT1 NY"  
"ESO DET OUT1 OVSCX"  
"ESO DET OUT1 OVSCY"  
"ESO DET OUT1 PRSCX"  
"ESO DET OUT1 PRSCY"  
"ESO DET OUT2 X"  
"ESO DET OUT2 Y"  
"ESO DET OUT2 NX"  
"ESO DET OUT2 NY"  
"ESO DET OUT2 OVSCX"  
"ESO DET OUT2 OVSCY"  
"ESO DET OUT2 PRSCX"  
"ESO DET OUT2 PRSCY"  
"ESO DET BINX"  
"ESO DET BINY"  
"ESO DET OUT1 X"  
"ESO DET OUT1 Y"  
"ESO DET OUT1 NX"  
"ESO DET OUT1 NY"  
"ESO DET OUT1 OVSCX"  
"ESO DET OUT1 OVSCY"  
"ESO DET OUT1 PRSCX"  
"ESO DET OUT1 PRSCY"  
"ESO DET OUT2 X"  
"ESO DET OUT2 Y"  
"ESO DET OUT2 NX"  
"ESO DET OUT2 NY"  
"ESO DET OUT2 OVSCX"  
"ESO DET OUT2 OVSCY"  
"ESO DET OUT2 PRSCX"  
"ESO DET OUT2 PRSCY"

## 4.2 Static Calibration Data

All static calibration data for SPHERE can be found in the calibdata subdirectory. The static calibration data for the different three subsystems are located in sphere-0.14.1/spherecal. The current static calibration data available for SPHERE are the IRDIS and IFS instrument models.

| Parameter / Keyword                  | Default Value                     | Description                                                                                                |
|--------------------------------------|-----------------------------------|------------------------------------------------------------------------------------------------------------|
| HIERARCH ESO DRS IFS DET PIX SIZE    | 2048                              | The detector size in pixels                                                                                |
| HIERARCH ESO DRS IFS LENS N SIDE     | 145                               | The number of lenslets along one side of the BIGRE                                                         |
| HIERARCH ESO DRS IFS LENS SIZE       | 161.5                             | The size of lenslets in microns                                                                            |
| HIERARCH ESO DRS IFS PIX SIZE        | 18                                | The size of detector pixels in microns                                                                     |
| HIERARCH ESO DRS IFS SPEC PIX LENGTH | 39.0                              | The model spectra size (in pixels)                                                                         |
| HIERARCH ESO DRS IFS SPEC PIX WIDTH  | 4.93                              | The model spectra width (in pixels)                                                                        |
| HIERARCH ESO DRS IFS ROTANGLE (§)    | -11.0                             | BIGRE rotation angle in degrees (ccw)                                                                      |
| HIERARCH ESO DRS IFS BIGRE SCALE     | $4.5957 \times 10^{-5}$           | The scale of the BIGRE - this determines the scaling from sky to instrumentcoordinates in arcsec / microns |
| HIERARCH ESO DRS IFS BIGRE ROT OFF   | -8.7691                           | BIGRE rotation offset angle in degrees (ccw)                                                               |
| HIERARCH ESO DRS IFS OFF X (§)       | 8.0                               | zero point offset in x (in pixels)                                                                         |
| HIERARCH ESO DRS IFS OFF Y (§)       | 2.0                               | zero point offset in y (in pixels)                                                                         |
| HIERARCH ESO DRS IFS SCALE X (§)     | 1                                 | Spectra pattern scaling in X                                                                               |
| HIERARCH ESO DRS IFS SCALE Y (§)     | 1                                 | Spectra pattern scaling in Y                                                                               |
| HIERARCH ESO DRS IFS MAX LAMBDA      | 1.677 (JH mode)<br>1.346 (J mode) | Maximum wavelength covered by spectra in microns                                                           |
| HIERARCH ESO DRS IFS MIN LAMBDA      | 0.951 (JH mode)<br>0.95 (J mode)  | Minimum wavelength covered by spectra in microns                                                           |
| HIERARCH ESO DRS IFS DISPERSON (*)   |                                   | Dispersion in microns / pixel                                                                              |

Table 4.1: IFS lenslet model parameters. Parameters marked with a (\*) are derived from other quantities and cannot be changed directly, parameters marked with a § are fitted for in the spectra positions recipe.

```
> ls -R calibdata calibdata: ifs irdis zimpol
calibdata/ifs: ifs_lenslet_model_Y_H.txt ifs_lenslet_model_Y_J.txt
calibdata/irdis: irdis_instrument_model.txt
calibdata/zimpol:
```

## 4.2.1 IFS lenslet model

Several recipes, in particular the wavelength calibration, spectra positions and IFU flat recipes require a model of the lenslet. This model describes how the lenslets are projected onto the detector in some standard dithering position (the “zero” position). In future version this may be extended to include other relevant IFS instrument model parameters, like filter parameters, etc. In the current version, the lenslet model can be provided either as header information in a FITS file or more easily as a simple ASCII text file which is written in the “ini” style format of “KEY = VALUE” pairs on each line.

### 4.2.1.1 Parameters of the IFS lenslet model

The IFS default lenslet model is given by the following parameters and values:

The IFS lenslet model may be given using a separate ASCII file. The standard default model for the J mode would be given in the following way:

```
[ ESO DRS IFS LENSLET MODEL ]
ESO DRS IFS DET PIX SIZE = 2048
ESO DRS IFS LENS N SIDE = 145
ESO DRS IFS PIX SIZE = 18.000000
ESO DRS IFS LENS SIZE = 161.500000
ESO DRS IFS SPEC PIX LEN = 39.000000
ESO DRS IFS SPEC PIX WIDTH = 4.930000
ESO DRS IFS ROTANGLE = -11.000000
ESO DRS IFS BIGRE SCALE = 0.000045957
ESO DRS IFS BIGRE ROT OFF = -8.769100
ESO DRS IFS OFF X = 2.000000
ESO DRS IFS OFF Y = 8.000000
ESO DRS IFS SCALE X = 1.000000
ESO DRS IFS SCALE Y = 1.000000
ESO DRS IFS MAX LAMBDA = 1.346000
ESO DRS IFS MIN LAMBDA = 0.950000
```

The meaning for the various parameters relating to the spectra (spectral length, minimum and maximum wavelength) are illustrated in Fig. 4.1. A cross section of a typical spectrum with a broad band lamp is shown at the top of the figure. Below, the diagram illustrates the meaning of the principal parameters and how the spectrum extraction works. The grey area marks the area as predicted from the lenslet model above, a box with the width and length as specified by the ESO DRS IFS SPEC PIX LEN and ESO DRS IFS SPEC PIX WIDTH parameters. The exact position of the spectrum on the detector is determined by the hexagonal arrangement of the BIGRE lenslet array and the ESO DRS IFS ROTANGLE, ESO DRS IFS ROT OFF, ESO DRS IFS OFF X, ESO DRS IFS OFF Y and ESO DRS IFS SCALE X and ESO DRS IFS SCALE Y parameters. These parameters are fitted for in the spectra positions recipe.

When extracting the spectra, only those pixels are extracted that fall fully inside the predicted spectra model region (the blue area in the diagram). Note that this means that, e.g. for a model spectra length of 39 pixels, the extracted region will always only be 38 pixels long. The minimum and maximum wavelength then refer to the midpoints of the first and last pixels in this model region. The minimum and maximum wavelengths of the model are “guidance” values only: the wavelength calibration recipe for IFS will determine the actual minimum and maximum wavelengths of each spectra region. The dispersion is calculated on the model spectrum and is  $\Delta\lambda = (\lambda_{max} - \lambda_{min}) / (L_{model} - 2)$ , where  $L_{model}$  is the model length of the spectra. As seen from the diagram, the length of the extracted spectra  $L_{extract} = L_{model} - 1$  if  $L_{model}$  is an integer value. In that case, the dispersion is:  $\Delta\lambda = (\lambda_{max} - \lambda_{min}) / (L_{extract} - 1)$ .

#### 4.2.2 IRDIS Instrument model

Similarly as for IFS, several recipes for IRDIS also rely on an “instrument model”. The IRDIS instrument model is much simpler and currently only contains information on the detector regions corresponding to the different optical paths (left and right paths). It is automatically created in the instrument flat recipe and the model information is stored in the header of the master instrument flat field. It is usually not needed to change this information. The model is valid for the “zero” dithering position. In future version the model may be extended to include other relevant IRDIS instrument model parameters, like filter parameters, etc. In the current version, the lenslet model can be provided most easily as a simple ASCII text file which is written in the “ini” style format of “KEY = VALUE” pairs on each line.

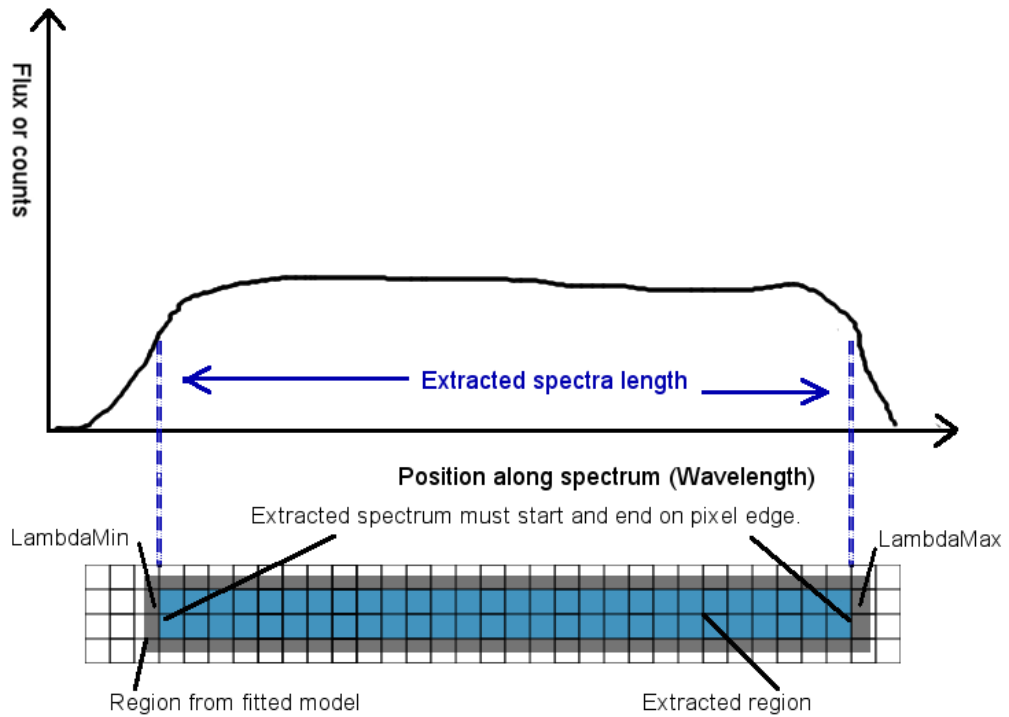


Figure 4.1: The spectra model and spectra extraction for IFS

## 4.3 Data Reduction Pipeline Data Products Format

### 4.3.1 Calibration Products Data Representation

For both IRDIS and IFS, the data reduction pipeline creates calibration products in a variety of formats. The two most general formats are described in this section, but see the description of the individual recipes for more detailed information and information on other data product formats.

#### 4.3.1.1 The SPHERE “master frame”

The most simple data product produced by the SPHERE pipeline consists of a FITS file with 4 extensions, all containing a single plane ( $N_{\text{AXIS}} = 2$ ) and all having the same number of pixels in both x and y (for IFS and IRDIS this will be  $N_{\text{AXIS1}} = N_{\text{AXIS2}} = 2048$  in most cases). The extensions have the following meaning:

| Extension Number | Type  | BITPIX | Meaning                                                 |
|------------------|-------|--------|---------------------------------------------------------|
| 1                | FLOAT | -32    | Image / Main values                                     |
| 2                | SHORT | 8      | Bad or flagged pixels (0 = ok, 1 = bad )                |
| 3                | FLOAT | -32    | Weightmap (e.g. number of pixels that went into result) |
| 4                | FLOAT | -32    | RMS Error / Other Error Info                            |

#### 4.3.1.2 Seeing double: The SPHERE double image

For all instruments several calibration (and also raw data) consist of two associated images. This is specifically true for IRDIS, which uses a double optical path close to the detector, and ZIMPOL which stores two interlaced separate images in one readout detector frame using pixel-shifting. Also for IFS some information, like the distortion vector of the lenslet array has an inherent two-component data structure. In nearly all such cases the SPHERE pipeline uses the same data format: a FITS file which consists of a total of 8 extensions. These 8 extensions are:

| Extension Number | Type  | BITPIX | Meaning                                                               |
|------------------|-------|--------|-----------------------------------------------------------------------|
| 1                | FLOAT | -32    | Image / Main values for “A” image                                     |
| 2                | SHORT | 8      | Bad or flagged pixels (0 = ok, 1 = bad ) for “A” image                |
| 3                | FLOAT | -32    | Weightmap (e.g. number of pixels that went into result) for “A” image |
| 4                | FLOAT | -32    | RMS Error / Other Error Info for “A” image                            |
| 5                | FLOAT | -32    | Image / Main values for “B” image                                     |
| 6                | SHORT | 8      | Bad or flagged pixels (0 = ok, 1 = bad ) for “B” image                |
| 7                | FLOAT | -32    | Weightmap (e.g. number of pixels that went into result) for “B” image |
| 8                | FLOAT | -32    | RMS Error / Other Error Info for “B” image                            |

In this table, the data represented by the “A” and “B” image depend on the specific instrument and

recipe: for example, for thesph\_ird\_science\_dpi recipe, the “A”image represents the intensity image, I, and image “B”the polarisation, P.

#### 4.3.1.3 The SPHERE quad image

Some of ZIMPOL instrument calibration output product consists of 4 associated images. This is the consequence of the fact that one zimpol exposure contains two interlaced images for both phases (0 and PI). Thus, a save quad image FITS file consist of a total of 16 extensions. The 16 extensions are:

| Extension Number | Type  | BITPIX | Meaning                                                                        |
|------------------|-------|--------|--------------------------------------------------------------------------------|
| 1                | FLOAT | -32    | Image / Main values for “A”image (phase 0)                                     |
| 2                | SHORT | 8      | Bad or flagged pixels (0 = ok, 1 = bad ) for “A”image (phase 0)                |
| 3                | FLOAT | -32    | Weightmap (e.g.number of pixels that went into result) for “A”image            |
| 4                | FLOAT | -32    | RMS Error / Other Error Info for “A”image (phase 0)                            |
| 5                | FLOAT | -32    | Image / Main values for “B”image (phase 0)                                     |
| 6                | SHORT | 8      | Bad or flagged pixels (0 = ok, 1 = bad ) for “B”image (phase PI)               |
| 7                | FLOAT | -32    | Weightmap (e.g.number of pixels that went into result) for “B”image(phase 0)   |
| 8                | FLOAT | -32    | RMS Error / Other Error Info for “B”image (phase 0)                            |
| 9                | FLOAT | -32    | Image / Main values for “A”image (phase PI)                                    |
| 10               | SHORT | 8      | Bad or flagged pixels (0 = ok, 1 = bad ) for “A”image (phase PI)               |
| 11               | FLOAT | -32    | Weightmap (e.g.number of pixels that went into result) for “A”image (phase PI) |
| 12               | FLOAT | -32    | RMS Error / Other Error Info for “A”image ((phase PI)                          |
| 13               | FLOAT | -32    | Image / Main values for “B”image (phase PI)                                    |
| 14               | SHORT | 8      | Bad or flagged pixels (0 = ok, 1 = bad ) for “B”image                          |
| 15               | FLOAT | -32    | Weightmap (e.g.number of pixels that went into result) for “B”image(phase PI)  |
| 16               | FLOAT | -32    | RMS Error / Other Error Info for “B”image (phase PI)                           |

The quad image format is currently used for the new version of the ZIMPOLmaster bias and master dark.

## Chapter 5

# Mathematical Description

Here we describe the mathematical algorithms that are used for data reduction. In addition, this chapter serves as an overview of the general data reduction process.

### 5.1 Signal propagation through DRH

For a scientific exposure, the most general observation mode for SPHERE, the scientific signal as given by an input flux  $S(\alpha, \beta, \lambda)$  results in a detector image,  $I(x, y)$  that represents the electrons received by the detector and converted into counts including all instrumental effects. Here the physical (or “sky”) coordinates  $\alpha, \beta$  are transformed onto the detector pixels  $x, y$  through the dispersive elements, with the mapping

$$S(x, y) = S(x_{\Delta x, \Delta y}(\alpha, \beta, \lambda), y_{\Delta x, \Delta y}(\alpha, \beta, \lambda)),$$

with the pixel to lenslet associations  $x_{\Delta x, \Delta y}(\alpha, \beta, \lambda)$  and  $y_{\Delta x, \Delta y}(\alpha, \beta, \lambda)$ . These pixel to lenslet associations depend on the relative offset between lenslet array and detector,  $\Delta x$  and  $\Delta y$  and are determined during the wavelength calibration procedures. We will henceforth write  $S(x, y; \lambda)$  for  $S(x_{\Delta x, \Delta y}(\alpha, \beta, \lambda), y_{\Delta x, \Delta y}(\alpha, \beta, \lambda))$ , representing the pixelised science image, i.e. a 2-D detector image of the lenslet array that is devoid of instrumental effects. We write the  $\lambda$  dependence here as a reminder that this is a 2D representation of a wavelength cube.

From the entrance into the telescope the scientific signal is affected by several components in an adverse manner, and all these effects have to be removed by the data reduction process in order to achieve maximal scientific output. This is achieved by applying several transformations to the detected image,  $I(x, y)$  to reverse the actions of the instrumental and telescope effects. These transformations are in general applied in a sequential manner, reflecting the physical layout of the detecting system, which consists of several components each of which affects the input signal in series. However, it is important to keep this assumption of “sequentially” which underlies most of the principles of astronomical data reduction in mind. In order to allow the removal of the various effects by the instrument/telescope components, one attempts to isolate and measure the effect of each individual component in a calibration procedure which is executed in a separate step to the science observation, either at various times during the observation night, during the preceding day or only at specific times throughout the year.

The data reduction handling for the IFS subsystem of SPHERE provides calibration procedures to measure and correct for the most important instrumental effects. Realizing that the IFS system can essentially be broken down into three relevant parts: the detector including readout electronics, the instrument, including optical components like lenslets and the telescope, including the SPHERE “common path”, the signal propagation can be represented by a series of components that act on



Figure 5.1: Schematic representation of the hardware components for IFS from a DRH point of view. The signal is affected by various hardware components which are calibrated out on the data reduction process. For each component the basic mathematical effect is given either as addition, division or multiplication. The first left most effects are all included in the “science” signal  $S(x, y; \lambda)$  below.

the input signal  $S(x, y; \lambda)$ . We show these components schematically in Fig 3.1. Mathematically the signal propagation can be represented with the following equation:

$$I(x, y) = G \times \{DC(x, y) \times \Delta t + B(x, y) + DF(x, y, \lambda) \times IF(x, y, \Delta x, \Delta y, \lambda) \times S(x, y; \lambda)\} + RON, \quad (5.1)$$

where  $G$  is the total gain,  $DC$  the dark current,  $B$  the bias,  $DF$  the detector flat response,  $IF$  the instrument flat response,  $RON$  the readout noise,  $\Delta x$  the detector dither offset in  $x$ ,  $\Delta y$  the detector offset in  $y$ . The exposure time,  $\Delta t$  has the special property (due to the detector technology) that

$$\Delta t = n \times T, \quad n \geq 1,$$

where  $T$  is a constant exposure time unit, around 1.3sec. Note that  $n \geq 1$  and so an exposure time of  $\Delta t = 0$  is not possible. This also means that a “bias”, defined as the detector response for zero exposure time, can not be measured directly for IFS and IRDIS but has to be inferred.

All the functions for the system components,  $DC$ ,  $B$ ,  $DF$ ,  $IF$  and  $TF$  are written in detector pixel coordinates, even if the corresponding calibrations may be detector position independent. For example, the instrument flat field is the effect of the lenslet array on the signal, which is a function of lenslet and wavelength but is independent on the detector position. The signal as received in detector pixel coordinates, however, is dependent on the detector offset simply due to a shift in coordinate system. In this sense the functions for the system components defined in the equation above rather represent the detected signal on the detector if all other contributions are zero. The response functions of the detector, the instrument and the telescope are assumed to be linear in the signal  $S$ . Linearity of these components, for signals in unsaturated regimes, is part of the SPHERE hardware requirement specification and the linearity assumption is therefore in general justified. An exception are image ghosts (due to optical reflections) and persistence effects.

## 5.2 Signal propagation reversal

Given the above signal response equation, the inverse can be formulated to infer the original science signal from the detected image:

$$S(x, y; \lambda) = \frac{[I(x, y) - RON] / G - DC(x, y) \times \Delta t - B(x, y)}{DF(x, y, \lambda) \times IF(x, y, \Delta x, \Delta y, \lambda) \times TF(x, y, \Delta x, \Delta y, \lambda)}.$$

The statistical mean of the readout noise should be zero (by choice), simplifying the equation slightly to:

$$S(x, y; \lambda) = \frac{I(x, y) / G - DC(x, y) \times \Delta t - B(x, y)}{DF(x, y, \lambda) \times IF(x, y, \Delta x, \Delta y, \lambda) \times TF(x, y, \Delta x, \Delta y, \lambda)}. \quad (5.2)$$

Knowledge of the functions  $DC$ ,  $B$ ,  $DF$ ,  $IF$  and  $TF$  and the gain allows one then to determine the scientific signal from the observed detector image. The various functions are determined in the calibration procedures by isolating the relevant components, using a known input source signal  $S$  and processing the detector image.

## 5.3 Signal propagation for bias and dark calibrations

The signal propagation for bias and dark calibration is very simple since the signal  $S$  is zero:

$$I(x, y) = G \times [DC(x, y) \times \Delta t + B(x, y)] + RON.$$

Assuming that the statistical mean of the readout noise is zero, the bias and dark term can simply be obtained as

$$DC(x, y) \times \Delta t + B(x, y) = I(x, y)/G.$$

Thus, taking an exposure with closed shutters and dividing by the gain, directly gives the dark+bias contribution. However, note that this depends on the exposure time. Also, since conversion from electrons to counts in the detector also depends on the readout mode, a bias+dark measurement is required for each exposure time and readout mode used in any observation which is to be processed. This is generally true for all detector effects and will be neglected in the further treatment in this chapter (the only consequence is that every measurement is performed for each possible combination of exposure time and readout mode). In the case that a separate measurement of the components  $DC$  and  $B$  is required, the following description can be used: repeatedly expose the detector for different times  $\Delta t$  thereby obtaining  $I(x, y, \Delta t)$  and perform a linear fit to the observed count,  $I(x, y, \Delta t) = k(x, y) \times \Delta t + b(x, y)$ . Comparison with the above equation directly yields the dark and bias components. Note that this procedure is necessary because an exposure time of 0s is not possible for the infrared detector and so the bias can not be measured using 0s exposures as for optical CCDs.

### 5.3.1 A special note about the dark calibration and the use of the word “dark” in this document

Even though the calibration plan foresees a master “dark” calibration, and the calibration as well as the result is referred to as “dark calibration” and “dark” or “master dark” throughout this document, this is not really the correct terminology that should be used for this recipe in the case of IRDIS and IFS. Since the dark current is very low for IR detectors, both IRDIS and IFS, what is actually calibrated in this recipe is the so called “Fixed Pattern Noise”, or FPN, which represents the spatial variation of the response of pixels to a zero input stimulus. This is dependent on integration time as well as read out mode and may vary on relatively short timescales. To keep with the terminology of the calibration plan we shall continue to refer to this calibration as the “dark” calibration also for the infrared detectors of IFS and IRDIS.

## 5.4 Signal propagation for the detector flat field

In this case, the detector is illuminated with a uniform lamp of a given wavelength, giving a signal  $S(x, y; \lambda) = L(\lambda)$  that is uniform over the detector and depends only on the wavelength, or, more generally, on the spectral energy distribution of the lamp used. Since neither the instrument components (lenslet arrays) or the telescope are involved the detected image is given by:

$$I(x, y) = G \times \{DC(x, y) \times \Delta t + B(x, y) + DF(x, y, \lambda) \times L(\lambda)\} + RON.$$

Knowledge of the bias and dark component from previous measurements, and exploiting the statistical mean of the readout noise of zero gives:

$$DF(x, y, \lambda) = \frac{I(x, y, \lambda)/G - DC(x, y) \times \Delta t - B(x, y)}{L(\lambda)}.$$



This means that the detector flat field response for a given wavelength is measured by taking an exposure of time  $\Delta t$  and subtracting a bias+dark calibration frame with the same exposure time. In general the lamps used for calibration purposes are not perfectly monochromatic, and some detector flats are even taken with a white lamp, giving:

$$DF_L(x, y) = \int [(I(x, y, \lambda)/G - DC(x, y) \times \Delta t - B(x, y))/L(\lambda)] d\lambda,$$

where  $L(\lambda)$  is the normalized wavelength emission of the calibration lamp  $L$  used. Since the actual quantity required in equation 5.2 is  $DF(x, y, \lambda)$ , it is necessary to extrapolate from a series of  $DF_L(x, y)$  for different calibration lamps,  $L = 1 \dots N$ . In practice, the calibration lamps used for SPHERE have a small bandwidth and can be assumed to be monochromatic (except for the broad band lamp), giving directly  $DF(x, y, \lambda_L)$ . Since only a finite number of such calibration lamps are available, it is not possible to determine  $DF(x, y, \lambda)$  for every wavelength directly. Rather, determination of  $DF_L(x, y)$  for all monochromatic calibration lamps can be used to construct a fit function for every pixel,  $f_{x,y}(\lambda)$  which in turn can be used to construct an estimate of  $DF(x, y, \lambda)$  for every wavelength. The accuracy of this then depends on the number of monochromatic calibration lamps used, and how well the wavelength dependence of the pixel response can be described by the fitting function chosen.

## 5.5 Signal propagation for the instrument flat field

### 5.5.1 Instrument flat field for IFS

For the instrument flat field for the IFS, the set-up is similar to the detector flat field, except that the lenslet array and some related optical components are in the light path. The equation for the signal propagation, eq. 5.1 becomes:

$$I(x, y) = G \times \{DC(x, y) \times \Delta t + B(x, y) + DF(x, y, \lambda) \times IF(x, y, \Delta x, \Delta y, \lambda) \times L(\lambda)\},$$

where  $L(\lambda)$  is the spectral energy distribution of the calibration lamp and we have assumed that the mean of the readout noise is zero. Now, the calibration measurement is the same as that for the detector flat field, except that we now measure the product  $DF(x, y, \lambda) \times IF(x, y, \Delta x, \Delta y, \lambda)$  instead of just  $DF(x, y, \lambda)$ . Since no lenslet array is used in the detector flat exposure, detector flats are independent of the detector position. However, the pixel associated is detector position dependent, and so, in order to measure  $IF(x, y, \lambda)$  the pixel positions have to be remapped through the pixel description table before a detector flat is divided out. The main purpose of the `sph_ifs_instrument_flat` recipe described later is to create a calibration frame which contains only the  $IF(x, y, \lambda)$  part and is detector position independent. These IFU flat calibration frames can simply be obtained in any detector position as long as detector flat fields taken at the same detector position are divided out. Again the limited availability of calibration lamps means that the wavelength dependence will be estimated by functional fits,  $f_{x,y}(\lambda)$ , to a series of measurements at the different calibration wavelengths, such that

$$DF(x, y, \lambda) \times IF(x, y, \Delta x, \Delta y, \lambda) = f_{x,y,\Delta x,\Delta y}(\lambda). \quad (5.3)$$

Recipes that need to correct for the instrument flat field use a set of master input detector flat fields in combination with the detector position independent master IFU flat field to construct the function  $f_{x,y,\Delta x,\Delta y}(\lambda)$ . Which fitting function to use is decided within the recipe and may be a parameter to the recipe plugin. We should note here, that the  $\lambda$  dependence of the lenslet response is expected to be small – and it may in principle be possible to simplify the data reduction process in this case.

For IFS the quantity on the left hand side of equation 5.3 multiplied by the wavelength association mask as obtained during the wavelength calibration (described further below)

$$SF(x, y) \equiv \int DF(x, y, \lambda) \times IF(x, y, \Delta x, \Delta y, \lambda) \times \delta(\lambda - \lambda_{x,y}) d\lambda \quad (5.4)$$

is referred to as the “Super Flat”. In the equation defining  $SF(x,y)$   $\delta(\lambda)$  is the Dirac delta function and  $\lambda_{x,y}$  is the wavelength associated with the pixel at  $x,y$  through the wavelength calibration. This quantity is measured directly in the `sph_ifs_instrument_flat` recipe, but we reiterate that for reduction of IFS science frames it is not enough to measure the quantity  $SF(x,y)$  in one single calibration since the different quantities entering  $S(x,y)$  vary on different timescales. Therefore the super flat is reconstructed from separate master calibration files of  $DF$ ,  $IF$  and the wavelength calibration within all science observation and calibration data reductions. Also note that  $SF(x,y)$  is dither position dependent.

### 5.5.2 Instrument flat for IRDIS

For IRDIS there is no detector flat field, and there exists only the instrument flat field calibration. Also, since the main observing modes for IRDIS are imaging modes, the wavelength dependence is implicit only and the instrument flat field becomes

$$FF_{imaging}(x, y; F) \equiv \int DF(x, y, \lambda) \times IF(x, y, \Delta x, \Delta y, \lambda) \times F(\lambda) d\lambda, \quad (5.5)$$

where the flat quantity  $F(\lambda)$  is the filter transmission curve. For the DBI mode, the filter will be different for the left and right sub-windows of the detector. Again, note that for IRDIS, as opposed to IFS, the quantity  $DF$  and  $IF$  are not measured separately, but only  $FF(x, y; F)$  is measured. This also means that  $I$  is, strictly speaking, dithering dependent.

For the spectroscopy mode, the flat field is defined in an analogous way to IFS as

$$FF_{spec}(x, y; F) \equiv \int DF(x, y, \lambda) \times IF(x, y, \Delta x, \Delta y, \lambda) \times F(\lambda) \times \delta(\lambda - \lambda_{x,y}) d\lambda. \quad (5.6)$$

Again, the flat field is measured in its entirety. It is therefore both filter as well as dithering dependent.

## 5.6 Finding spectral regions in IFS

For the IFU capabilities of the IFS it is necessary to identify all the regions where spectra fall onto the detector in an automatic way. In principle this needs to be done for every possible detector position in a separate calibration step implemented as the `sph_ifs_spectra_positions` in the data reduction library. However, the creation of detector position dependent PDTs is done purely in the data reduction recipes: only one “master” PDT table for the standard dithering position is created during calibrations. PDTs for other dithering position are calculated from the dithering position and this master PDT. The simplest algorithm for detecting spectral regions proceeds as follows:

1. Create dark subtracted master calibration frames from the input raw frames. Bad pixels must be flagged/set to zero.
2. Divide this frame by a master detector flat field taken with the broad band (white light) lamp.

3. Apply a threshold algorithm to identify regions with pixel values above a certain threshold value.
4. Assign a label for each connected region.
5. Associate these regions from the regions as expected from a model of the lenslet array. Regions that are either associated to two different lenslet IDs or that have no lenslet ID associated from model are counted and marked.
6. Save label information for each pixel in the pixel description table (PDT). Pixels outside spectral regions are given label 0.

The advantage of this procedure is that it is very simple and the spectral regions have been identified using a clear criterion. This procedure is also very robust to “missing” lenslets or gaps. However, this simple minded approach has the disadvantage of requiring a flat spectra response, that is, the signal along a spectrum must be high and the contrast with regions that do not contain spectra must be high. This is not always the case, since the detector is likely to have a strongly wavelength dependent sensitivity the spectra will not be flat on the detector and in some regions the detector sensitivity may be so low that the contrast is not high enough. In addition this procedure does not take account of the fact that the boundary of spectra do not fall exactly in between pixels; some pixels will be illuminated partly by a spectrum, further reducing the contrast with un-illuminated regions. All this means that the performance of this procedure depends rather critically on the choice of the threshold parameter.

An alternative approach, used in the current SPHERE pipeline, uses a model function of the spectra locations to improve on the simple thresholding approach. This model can be provided simply as an image,  $M(x', y')$ , where

$$M(x', y') = \begin{cases} 0 & \text{off spectra} \\ 1 & \text{on spectra} \end{cases},$$

The determination of spectral regions on the observed detector image,  $I(x, y)$  then just becomes an optimization problem for finding the offset between  $\Delta x = x' - x$  and  $\Delta y = y' - y$  such that the difference in observed illuminated and predicted spectral regions is minimal and, ideally,

$$I(x + \Delta x, y + \Delta y) = M(x', y').$$

The model itself is derived from the IFS instrument model as described in 4.2.1.

## 5.7 The IFS wavelength cube and IFS wavelength calibrations

### 5.7.1 The wavelength cube

For science data reduction purposes of IFU data it is necessary to perform a series of wavelength calibration procedures. Regions on the detector have to be identified where the spectra fall on and every pixel has to be corrected for the wavelength dependent effects. In general, any IFU data at spatial coordinates  $\alpha, \beta$  and at wavelength  $\lambda$  will be constructed from a detector image  $I(x, y)$  (obtained with the lenslet array in the optical path) in the following way:

$$IFU(\alpha, \beta, \lambda) = I(x_{\Delta x, \Delta y}(\alpha, \beta, \lambda), y_{\Delta x, \Delta y}(\alpha, \beta, \lambda)),$$

with the pixel to lenslet associations  $x_{\Delta x, \Delta y}(\alpha, \beta, \lambda)$  and  $y_{\Delta x, \Delta y}(\alpha, \beta, \lambda)$ . These pixel to lenslet associations depend on the relative offset between lenslet array and detector and are determined during

the spectra positions procedures described in section 3.6. In order to associate the detector pixels with the correct wavelength, a known line spectrum is used to illuminate the detector. Spectral regions are identified and a fit is performed to determine the pixel coordinates of the known line centers of the spectrum. For every lenslet spectrum a table associating the line wavelengths with pixels information is constructed and a fitting/interpolation procedure is used to associate wavelengths for all pixels in between. In this way every pixel will be associated with a lenslet (i.e.  $\alpha$  and  $\beta$  coordinates) and a wavelength. Since the procedure makes use of the same instrument set-up as used for the instrument flat procedures the resulting detector image is:

$$I_{\Delta x, \Delta y}(x, y) = G \times \{DC(x, y) \times \Delta t + B(x, y) + DF(x, y, \lambda) \times IF(x, y, \Delta x, \Delta y, \lambda) \times S(x, y; \lambda)\}.$$

However, contrary to the instrument flat field procedure we are not interested in obtaining  $I(x, y, \lambda)$  but rather, we wish to obtain  $S(x, y; \lambda)$ , the “true” input signal, i.e. the idealized projection of the spectra after having gone through the lenslet array. Using the reversed propagation equation 5.2, we can write

$$S_{\Delta x, \Delta y}(x, y; \lambda) = \frac{I(x, y)/G - DC(x, y) \times \Delta t - B(x, y)}{DF(x, y, \lambda) \times IF(x, y, \Delta x, \Delta y, \lambda)}.$$

Thus, a reconstruction of  $S(x, y; \lambda)$  can be achieved if the bias and dark current  $DC(x, y)\Delta t + B(x, y)$  as well as the instrument flat  $DF(x, y, \lambda) \times IF(x, y, \Delta x, \Delta y, \lambda)$  are measured accurately. When a white flat field lamp is used as the illumination source the “detector representation” of  $S(x, y; \lambda)$  corresponds to the “super flat”  $S(x, y)$  defined above.

## 5.7.2 Wavelength calibration

At the wavelength calibration stage, the information of the pixel to wavelength associations is not yet available (that is rather the result or purpose of the wavelength calibration) the flat fielding has to be performed here using a IFS flat field frame which has not been divided by the detector flat, but is a measure of both detector and IFU flat. That is, DF and IF are not known separately, but rather together. The quantity  $DF(x, y, \lambda) \times IF(x, y, \Delta x, \Delta y, \lambda)$  integrated over the associated pixel wavelengths is just the super flat field defined in 5.3. So, as a first step, after dark subtraction, the raw wavelength calibration frames are divided by the super flat field (as measured directly in the sph\_ifs\_instrument\_flat recipe).

The flat fielded signal,  $S_{\Delta x, \Delta y}(x, y; \lambda)$  is then analysed to detect the spectral lines of the wavelength calibration lamp. The calibration lamp produces very sharp, monochromatic lines. The line profile as observed on the detector are a convolution of the intrinsic line profile, negligible for the calibration lamp lines used, and the instrumental profile (spectrograph resolution). Therefore, the expected line width for these new calibration hardware will be entirely given by the spectrograph resolution (about 2 pixels). Since the calibration lines are sharp, there is a possibility of some additional faint lines due to fringing, and so the positions on the spectra lines have to be determined by pre-selecting the regions close to the expected positions of the lines to avoid the fitting to be performed on some of these fringes (present as local maxima). Alternatively, the data extracted from the spectra region is first passed through a low pass filter to smooth out fringes before fitting is performed—before de-convolving again to assure that the measured FWHM is not affected. The line fringing is not expected to be an important effect for IFS, where spectra resolution is low, but for IRDIS MRS spectroscopy line fringing has to be taken into account. Only the first, simplest method is currently implemented. The peak position for each line is determined by calculating the weighted mean position for a window of a few pixels size around the expected line position. The expected line position is taken from an input model of the spectra positions and the dispersion. Since this input can also be another wavelength calibration product, the wavelength calibration can in principle be performed iteratively.

Once the line positions have been identified, a polynomial of degree  $P > 0$  is used to fit the curve of known line wavelengths to measured pixel coordinates. This fit is then used to fill all pixels not covered by lines with wavelength information. If  $P > 1$  the second derivative is used to estimate the dispersion.<sup>1</sup>

## 5.8 Further spectral and flux calibrations

The IFS uses IFU capabilities to create a wavelength data cube as the main science product of every observation. This wavelength data cube needs to be, as much as possible, free of instrumental effects and measure as accurately as feasible the true spectrum of the source. However, the observed spectrum is, just like the detector image, affected by several unwanted effects: the atmosphere as well as telescope subsystem introduce wavelength dependent effects. The observed spectrum is given by:

$$F_{obs}(\lambda; z, r, \theta) = F_{real}(\lambda) \times A_{atm}(\lambda; z) \times A_{corono}(\lambda; r, \theta) \times A_{tel}(\lambda; r, \theta) + T_{atm}(\lambda; z), \quad (5.7)$$

where  $A_{atm}(\lambda; z)$ ,  $A_{corono}(\lambda; r, \theta)$  and  $A_{tel}(\lambda; r, \theta)$  are the attenuation effects of the atmosphere, the coronagraph and the telescope, respectively,  $T_{atm}(\lambda; z)$  is the atmospheric transmission at wavelength  $\lambda$  and  $F_{real}(\lambda)$  is the true scientific signal to detect, which needs to be reconstructed in the calibration procedure. In order to be able to do this, without the need to obtain calibration frames for every science exposure, it is necessary to model the various instrumental and atmospheric effects individually and measure the relative contributions and model parameters at regular intervals. To this end, the various effects can be disentangled making use of the different dependencies: the atmospheric effects depend on airmass,  $z$  but are independent of source location on the detector, whereas telescope and coronagraph affect the signal dependent on the source position within the frame but are independent of air mass. The various components are modeled and calibrated as follows.

### 5.8.1 Atmospheric absorption

In order to remove the atmospheric dependence, it is necessary to use a spectral model of a known observed source. To avoid a strong dependence of the data reduction pipeline on model dependent quantities, the recipes for atmospheric calibration currently produce simplified reduced science frames. These have to be processed further by e.g. dividing by the known star spectra to obtain the atmospheric contribution.

### 5.8.2 Coronagraph effects

In general, the contribution of the coronagraph is not removed. Frames are processed without division by the coronagraph attenuation to reduce the impact that the incorrect removal of its effect may have on the data quality.

In the rare cases where a removal of the coronagraph effect is explicitly required, exposures can be taken with and without coronagraph and the ratio of the resulting spectra gives directly the coronagraphic effect (except for an unknown normalization constant). However, the fact that measurements are necessary at different points in the field makes this rather problematic if no good

<sup>1</sup>Alternatively, a dispersion model which gives the dispersion as a function of wavelength,  $D(\lambda)$  is used to create a “guess” pattern of line positions for each lenslet, and this pattern is matched to the observed line pattern (allowing for positional shifts). The “goodness” of fit of the pattern is calculated for each lenslet and can be used to monitor the dispersion stability of the lenslets. The dispersion  $D(\lambda)$  model can also be created as an output of the wavelength calibration when the polynomial fit is used to obtain line positions; the wavelength calibration can in fact be regarded as a measurement of the dispersion for each lenslet.

model of the coronagraphic effect with few parameters is found. It should be possible to determine a functional model,  $A_{corono}(\lambda, r, \theta; \alpha_0, \alpha_1, \dots, \alpha_N)$  with  $N$  parameters  $\alpha_0, \dots, \alpha_N$ , and  $N$  being a small number. The parameters of the model and verification will have to be determined in the first weeks after or during commissioning.

### 5.8.3 Instrumental background and sky background

In 5.1 no additive effects are included except those arising from the detector. However, there are signal contributions from both the sky and the instrument itself which need to be removed in order to obtain the true science signal. Since these are additive effects, they need to be subtracted out after the reverse propagation equation above, 5.2 has been applied. The total signal is

$$S_{tot}(x, y; \lambda) = S_{sky}(x, y; \lambda) + S_{ins}(x, y; \lambda) + S_{sci}(x, y; \lambda),$$

where  $S_{sky}$  is the sky background,  $S_{ins}$  is the instrument background and  $S_{sci}$  is the actual science signal. Note that these signals are additive – and so the calibration/removal of the sky and instrument background follows a similar procedure to the dark calibration, in the sense that they are subtracted from the input frames. Also note that all contributions have a wavelength dependence.

For IFS the contributions of the sky and instrument background are expected to be small and unimportant for the main science objective: the detection and imaging of planets. It is only in special cases, for example when extended sources are observed, that the sky and instrument background may significantly affect the science goal of the observations. Therefore, even though recipes are included in the pipeline to calibrate these effects, their applicability will be limited.

### 5.8.4 Flux normalization calibration

Since the above calibrations are all performed using ratios, it is not possible to determine in this way the absolute flux. In order to do this, one needs to observe a known source and compare total received flux (i.e. detector counts) with the known flux of the source. This requires a separate calibration procedure: sph\_ifs\_std\_phot and sph\_ird\_ins\_throughput. For more details, see the description of the recipes.

## 5.9 Time dependency impact of systems

In the above treatment of the signal propagation for the individual calibrations, we have not discussed the effect of time variation in the various detector, instrument and telescope systems. None of these systems are perfectly stable in time, meaning that it is necessary to repeat calibration procedures at time intervals which are less than the stability time-scale for the required accuracy. For example, the detector flat field is stable to within 0.1% only for about one hour. This means that the recipes that need to correct for effects that involve the  $DF(x, y, \lambda)$  term need to use calibration measurements of this quantity that are maximally one hour old. An alternative in such cases is to use monitoring measurements to construct a model of the time behaviour of the relevant subsystems. In the following table, we list approximate dependencies of the calibration terms:



| Term                | Variable dependence | Time-scale | Variation |
|---------------------|---------------------|------------|-----------|
| $DC(x, y)$          | $x, y$              | 1 day      | 1%        |
| $B(x, y)$           | $x, y$              | 1 day      | 1%        |
| $DF(x, y, \lambda)$ | $x, y$              | 30 mins    | 0.1%      |
| $DF(x, y, \lambda)$ | $\lambda$           | 1 week     | 0.1%      |
| $IF(x, y, \lambda)$ | $x, y$              | 1 day      | 0.1%      |
| $IF(x, y, \lambda)$ | $\lambda$           | 1 month    | 0.1%      |
| $TF(x, y, \lambda)$ | $x, y$              | 1 week     | 1%        |
| $TF(x, y, \lambda)$ | $\lambda$           | 1 month    | 1%        |

It is the responsibility of the observer to make sure that the frames used for the calibrations have the required “freshness”– the pipelines will make no checks for that. Also note that some calibration procedures measure quantities that are combinations of terms with different time variability. In these cases, the acceptable time-scale is given by the smallest acceptable time-scale of the subsystems involved. For example, the instrument flat field procedure measures the term  $DF(x, y, \lambda) \times IF(x, y, \lambda)$  which has an acceptable time scale for stability of about 30 mins - 1 hour. In some cases, it is also possible to model the time variability in such a way that only part of the procedure has to be performed in frequent intervals. For example, to perform accurate removal of the detector flat field in wavelength calibration it is in principle necessary to have detector flat-frames for all 4 calibration lamps that are all newer than 1 hour. However, modeling the behaviour of the detector flat field as

$$DF(x, y, \lambda) = DF(x, y) \times f(\lambda),$$

and noting that the detector response is very stable in terms of the wavelength dependence,  $f(\lambda)$  is almost constant over time, it is possible to only perform measurements of  $D(x, y)$  frequently, which requires taking calibration data with only a single lamp. This is the approach taken in SPHERE.

## 5.10 Clean Mean Algorithm: Basic Frame Combination with outlier rejection

Please note that the spatial derivative pixel rejection described below has not been implemented in SPHERE.

The clean mean algorithm is used to average frames taking into account the possibility of bad pixels and outliers in individual frames. The quality of the detector linearity will therefore be an important contributor to the quality of the data reduction process in SPHERE. The goal is to achieve an optimal mean frame that is not affected by individual bad or outlying pixels at the same time as keeping the maximum amount of information.

We use iterative clean mean with sigma computation (following that described in ESO’s SINFONI Pipeline User Manual) as our baseline frame combination method. For this process, the user sets minimum and maximum allowable intensity values. For a stack of frames, values inside this range are then used to determine an intensity mean and standard deviation, for each pixel position. Pixels with values differing from the mean by  $k * std$  are removed. This process is re-iterated  $n$  times to generate a final mean-combined image.

We wrote an alternative frame combination script with the aim of achieving superior outlier rejection, compared to the clean mean method. This alternative procedure (presented in [RD2]) uses an iterative median/mean combination outlier rejection strategy that takes advantage of the spatial derivative of an image to better deal with variations from a changing PSF shape or small (sub-pixel) pointing errors. This is particularly important in regions where the PSF slope is steep: there, a small change in pointing or PSF shape could lead to pixel values being wrongly interpreted as outlier pixels. The spatial derivative method should be effective at dealing with such phenomena, as demonstrated in data reduction for Spitzer IRAC (see [RD3]) and HST ([RD4]).

The code operates by first conducting a biased-median-combination of input frames to create a *best estimate image*. “Biased median” refers to taking the value  $b$  positions below the median value, to deal with non-symmetrical noise sources like cosmic ray effects. From this *best estimate image*, *BEI*, a *spatial derivative array*, *SDA*, may be calculated using the following equation.

$$SDA(x, y) = \max_{abs} (BEI(x, y) \sim [BEI(x - 1, y), BEI(x + 1, y), BEI(x, y + 1), BEI(x, y - 1)]) \quad (5.8)$$

Going back to the original input frames, we remove any pixel that differs in value from the corresponding *best estimate image* pixel by more than  $k$  times the corresponding pixel value in the *SDA*. In other words, we reject original input frame pixels that meet the following condition.

$$|original - frame(x, y) \sim BEI(x, y)| > k \times SDA(x, y) \quad (5.9)$$

The now-corrected input images are then mean-combined to generate the final image.

## 5.11 Detector pixel linearity

This algorithm is used for example in the `sph_ifs_master_detector_flat` recipe to determine the detector linearity for each pixel.

The linearity measurement is used in all recipes where the detector response is assumed to be linear as part of the algorithm. This is the case for all recipes that divide out the detector flat field for example, since the exact detector response is a function of input signal, and extrapolation to the actual input signal from the available detector flat calibration frames is needed (the value  $DF(x, y, \lambda)$  in the equation 5.1 is just this linear detector coefficient).

Recipes that need to correct for the detector flat field actually use the detector pixel linearity for the flat fielding, since this gives the correction as a function of detector mean, rather than exposure time. The detector flat to correct for is a function of signal rather than integration time.

As part of this algorithm pixels are identified that do not conform with linearity requirements. Such pixels can also be regarded as “bad pixels” in the sense that their behaviour does not follow the expected behaviour – depending on the required accuracy such pixels may need to be excluded from a frame combination procedure. The identification of bad pixels using this method is possible both for dynamic and static bad pixel identification – but its main use is to identify static bad pixels. The algorithm itself only calculates the reduced  $\chi$ -square of linear fits to each pixel’s response and the linear coefficients. Recipes can then use this information to flag certain pixels as bad.

This method to identify bad pixels can also be used to check that the dynamic bad pixel identification works as required and that the dynamic bad pixel identification routine are not affecting further data calibration and reductions adversely.

To determine the detector pixel linearity for monitoring is responsibility part of the `sph_ifs_gain` recipe, where the response of every pixel to different signal levels is measured and a fit performed.

## 5.12 Bad Pixel Identification

Bad pixel identification in SPHERE happens on several levels and in several ways. First, there is a distinction between dynamic and static bad pixels. Static bad pixels are due to a property of the detector and are, as the name implies, unlikely to change with time. It may happen that a pixel changes its status from “good” to “bad” in terms of static bad pixel detection (i.e. the pixel breaks), but the converse should in general not occur. Dynamic bad pixels however vary from exposure to exposure. Identifying these is therefore responsibility for all algorithms that combine a set of raw frames into a smaller set of output frames, e.g. the CLEAN MEAN algorithm described in 5.10.

### 5.12.1 Static Bad Pixel Identification

The identification of static bad (dead or hot) pixels in the data reduction occurs usually during the master dark calibration recipe. When the master dark frames are created, a static bad pixel map is created in the following way:

1. The master dark calibration frames are created from the input frames. As described in section 7, a master dark is created for every exposure time and readout.
2. The individual frames are combined using the clean mean method, effectively removing temporary bad pixels that appear in only a few of the frames.
3. A threshold clipping is applied to the combined frames
4. A smoothed version is subtracted (this is an optional step)
5. A two-pass sigma clipping is applied

This routine ensures that static bad pixels are truly static and are not random chance events. However, note that a reliable identification of truly static pixels requires that the sigma threshold in identifying the bad pixels in each master calibration frame is chosen adequately and that there is a reasonable (i.e. more than about 3) number of exposure time set-ups in the input frames.

A second procedure to detect static bad pixels uses the detector linearity behaviour to determine bad pixels. During the `sph_ifs_detector_flat` fielding recipe, a detector linearity map is created (see 5.11). This map gives, for every pixel, a measure of the linearity (goodness of fit for a linear fit) and the linearity coefficient. This map can then be used to flag pixels as bad. Many recipes allow a parameter to control the threshold on the linearity to accept/reject pixels. The detector flat recipe itself creates a static bad pixel map in this way, which is the standard bad pixel map input for other recipes.

The static (or “hot”) bad pixel map identified using the first method, in the `sph_ifs_master_dark` recipe, is used primarily for monitoring purposes and to validate the static bad pixels identified in the `sph_ifs_master_detector_flat` field recipe. For that purpose the detector flat field recipe outputs a quality control parameter that measures the number of pixels that have been identified in one static bad pixel map, but not the other. A large number here usually means that the detector linearity performance has degraded.

### 5.12.2 Dynamic Bad Pixel Identification

Apart from static bad pixels due to faults in the detector, there are also dynamic bad pixels that are created by transient effects: most notably by cosmic rays. These are identified whenever raw frames are combined. Each frame combination routine, like the clean mean algorithm above, needs to reject pixels that are deemed as bad – in the case of the clean mean algorithm due to their value away from the mean value. Since bad pixels due to cosmic rays can affect neighboring pixels as well as the same pixel at a subsequent readout, all pixels around a bad pixel (in a cross shape) should also be flagged as bad as well in the subsequent frame. This happens, for pixels that are sufficiently outlying, automatically in the clean mean algorithm.

### 5.12.3 Bad pixel treatment in the IRDIS and ZIMPOL science recipes

The science reduction recipes for IRDIS and ZIMPOL use the bad pixel maps from the dark and the flat field recipes to set the bad pixels on the resulting reduced science images. The bad

pixels set in the science frames is always the union of all static bad pixel maps. Both IRDIS and ZIMPOL use geometric transformations as part of the usual science data reduction process (e.g. for differential imaging or to process dithered frames) and the bad pixel maps are transformed along with the image. The algorithm for transforming the bad pixel maps is purely geometric in any case even when the image data is transformed using an FFT. Due to serious artefacts that would arise if an FFT is performed on data containing many discontinuities arising from bad pixels, the science recipes interpolate the bad pixels before any transformation on the image data. The (also transformed) bad pixel map however is maintained and used to calculate a final bad pixel map on the fully reduced and combined science image that then shows as bad all pixels that had no valid input pixel information.

## 5.13 Field Center

For all SPHERE instruments accurate determination of the field center is important. The required accuracy currently is 3 mas with a goal of 1 mas. This is true in particular for all pupil stabilized (or fixed de-rotator) modes. Here frame combination as described in 3.14 requires de-rotation of raw frames and for this the rotation center needs to be determined accurately. The situation as given from the hardware is as follows:

- the DTTS loop and reference slopes calibration ensures that:
  - this center of rotation is also the photo center and
  - this is also the location of coronagraph (all of this with satisfactory accuracy  $< 0.5$  mas)
- the DTTS calibration (CPI-TEC-01) outputs the position on the IRDIS detector of the coronagraph (for its internal use)

Currently there are several different field center calibration strategies considered:

1. Calibration within science data reduction recipes: here one uses the science raw frames themselves and the fact that the coronagraph center can be easily determined by determining the center of the region masked by the coronagraph. The AO (DTTS loop) then ensures that this coronagraph center is also the rotation center. For frames taken without coronagraph the star center itself, which is easily determined by finding the peak and Gaussian fitting.
2. Calibration of the center in a dedicated recipe but using the input raw science observation frames. For IRDIS the star center calibration which uses 4 secondary diffraction peaks to extrapolate the center of the star and hence the rotation center.
3. Dedicated calibration recipe using an artificial source. An artificial illumination source is used to perform a dedicated calibration which determines the center of the coronagraph for all possible instrument set-ups. This would be a daytime calibration with a as yet to be determined frequency. A dedicated recipe would reduce these calibration images and return a reference field center to use for frame combination in science data reduction recipes.

Currently, option 2 has been implemented for IRDIS in the `sph_ird_star_center` recipe. Which of these will be implemented for IFS is still to be decided.

## 5.14 Frame combination: de-shifting and de-rotating

Frame combination is one of the most crucial steps in the SPHERE data reduction since accurate frame combination including de-shifting and de-rotation allows use of ADI, SDI and other more advanced planet finding algorithms.

In SPHERE the frame combination including de-rotation, scaling (for SDI) and de-shifting is intended to be an integral part of the pipeline on the other hand and to be flexible and modular on the other. This is realised by allowing the choice of frame-combination to be given as an input parameter to recipes, along with all relevant parameters needed for the frame combination algorithm. Currently only a simple ADI and SDI is implemented.

For IRDIS the algorithm of choice to de-shift, de-rotate and de-scale is the FFT. The exact FFT implementation is a separate module and de-coupled from the actual frame-combination code so it can be replaced with different implementation easily. Currently the FFT provided by FFTW is used. The GSL fft routines are also available using a switch (recompilation is necessary).

The FFT rotation routine is augmented by a filter to remove high frequency noise. This filter is a simple top-hat filter which removes all frequencies that have a k-value in the Fourier domain that is above a percentage F of the maximum k-value.

For IFS, the algorithm to de-rotate the individual monochromatic images uses the hexagonal lenslet array geometry and the algorithm GIMROS. GIMROS calculates overlaps between polygons to interpolate the lenslet image onto a rotated grid of hexagons.

### 5.14.1 GIMROS - Generic Image Rotation and Scaling

The GIMROS algorithm is specifically created to interpolate the image from a hexagonal grid onto a translated and/or rotated second hexagonal grid.

#### 5.14.1.1 The concept behind GIMROS

The "G" in GIMROS means Generic and indicates that the concept of rotating and scaling image data is somewhat generalized in this algorithm. Not as strictly tied to astronomical purposes like in the IPAC Montage package, where every pixel is projected onto the sky before being mapped onto a new pixel grid, but more general in the sense of allowing more pixel shapes. Of particular interest in SPHERE's context are of course the hexagonal pixels of IFS, but in principle GIMROS allows for all convex polygons as image base elements. In fact, an image representation suitable for GIMROS must be more complex than simply a matrix full of values plus a header that describes how the indices of matrix elements are related to image co-ordinates.

#### 5.14.1.2 Transforming an image with GIMROS

The primary transformation technique applied by GIMROS will be to map the input fluxes collected on the input pixel grid to a given output pixel grid. The calculation of the coordinates of the output pixel grid is determined by the transformation and usually not performed by GIMROS itself. A few helper routines may be devised that perform simple special transforms such as arbitrary rotation about an arbitrary centre, arbitrary shifts in arbitrary directions, and image scaling.

The flux value of any output pixel  $F(i)$  will be calculated as the sum over all overlapping input pixels flux values  $G(j)$  weighted with the overlap area:

$$F(i) = \frac{\sum G(j) a_{ij}}{\sum a_{ij}}$$

It is obvious that this technique is flux conserving as long as both images are completely and continuously covered with non-overlapping pixels. Gaps between pixels, particularly in the output image, may of course lead to losses of flux.

The overall algorithm of GIMROS then looks as follows:

```
for all output pixels :
  area_weight = 0
```

```

flux = 0
find all potentially overlapping input pixels
for current_input_pixel
in potentially_overlapping_input_pixels:
area = overlap_area(current_input_pixel, current_output_pixel)*
current_input_pixel.weight area_weight += area flux +=
current_input_pixel.flux * area
if flux != 0:
flux /= area_weight

```

The introduction of the `current_input_pixel.weight` allows for handling badpixel maps on the input side

The finding of the potentially overlapping input pixels can be done in the following way:

1. calculate all centre points of all (transformed) input and output polygons
2. find the longest distance between centres and any edge point throughout the input and output polygons
3. sort the pixel polygons by the distance of their centre point to the centre point of the output polygon
4. the potentially overlapping pixels are the ones where the distance is below  $2 \cdot d_{\max}$

The calculation of the overlap area is done by clipping the (transformed) input polygon to the output polygon and calculating the area of the resulting, clipped polygon. For details of this procedure, see <http://www.mpa.de/SPHERE/WIKI/pmwiki.php?n=DRH.FrameCombination>.

## 5.15 Creating wavelength cubes for IFS

One of the last reduction steps in producing calibrated science frames for IFS is to construct a wavelength data cube,  $S(\alpha, \beta, \lambda)$ . As described before, this is achieved using pixel-to-lenslet association tables. The interpretation of the resulting cubic structure is, however, not straightforward unless some additional geometric transformations are used. The reason is that the lenslet array has a hexagonal rather than rectangular structure. This means that every spatial  $x, y$  position in the wavelength cube has a non-trivial associated sky position  $\alpha, \beta$ . How this geometric transformation is performed depends on the level of science reduction. For the basic reduction there are two possible outputs: a result on a hexagonal grid as a FITS table, representing a hexagonal “cube” and a result on a (square) pixel cube. In each case, the way that the interpolation onto the output grid is performed depends on the observing mode: field or pupil-stabilized. We describe the general algorithm for creation of wavelength cube below.

The starting point for cube creation is in any case a series of detector images. Spectra have been identified using the `sph_ifs_spectra_locations` and `sph_ifs_wave_calib` routines, which have created a master pixel description table, describing pixel wavelength associations for the standard zero-point dithering position. For each dithering position used in the observations to combine, a new PDT has to be constructed. This is done purely in a software manner – calculating a new PDT for the offset position from the master PDT using the `sph_pixel_description_table_new_shift` function. These PDTs can then be used to extract a spectrum for every raw input frame – thus providing dither independent information. The extracted spectra are saved in a structure called a “lenslet description table” (LDT) which describes the data in terms of the lenslet “view” of IFS. The LDT is strongly linked to the IFS instrument model, described in 4.2.1. Extracting the spectra and moving to the lenslet view removes any dithering dependence and spectra can now be combined. This is done on a spectrum by spectrum basis. Once a final combined set of spectra has been created (one spectrum for each lenslet) the result is saved as a wavelength cube. For this, the hexagonal structure is interpolated onto a hexagonal grid. We have currently implemented a method based on GIMROS to project hexagons onto quadratic pixels.

## 5.16 Distortion map

The distortion map needs to be measured for IFS and IRDIS. For ZIMPOL no distortion map measurement is currently foreseen, but it may be added at a later stage. For IRDIS the distortion map measures the distortion of the actual detector,  $\Delta(x, y) = [\Delta_x(x, y), \Delta_y(x, y)]$ , defined by

$$S(x, y) = S'(x + \Delta_x(x, y), y + \Delta_y(x, y)) \quad (5.10)$$

where  $S(x, y)$  and  $S'(x, y)$  represent the distortion corrected and uncorrected signal respectively. For IFS the distortion map of the lenslet array itself is the relevant quantity, which is defined in an analogous way.

In both cases, the distortion is measured using a grid of artificial sources with known positions. The grid positions are used as an input to the distortion map recipe which detects the actual observed sources and measures their displacement with respect to the expected positions to obtain a vector map. The x and y component of this vector map is fit using a 2D polynomial, giving a smooth representation of the distortion map.

## 5.17 Astrometry and plate scale solution

The field of view for all SPHERE instruments is very small and astrometry for SPHERE is a two parameter problem: the rotation angle relative to the north direction and the pixel scale. The field center itself is determined in a separate recipe.

To allow the determination of the two parameters, a binary system needs to be observed. The relevant recipes reduced the raw observation frames and automatically detect the central star and the companion. Together with the user input parameters of angle and separation the angle to north and plate scale are derived.

## 5.18 ZIMPOL measurements

### 5.18.1 Definitions of terms used for ZIMPOL measurements

In this document and in the SPHERE ZIMPOL calibration plan (RD1), several expressions are used for describing specific parts of a ZIMPOL measurement. The different expressions aim to better distinguish between the entities they describe and are chosen according to ESO definitions described in AD1.

**Exposure:** In general, an *exposure* is the entity of one or more (NDIT) integrations (*frames*), followed by the readout and storage of the NDIT *frames*.

- For ZIMPOL polarimetric modes (P1, P2, P3), an *exposure* is always the entity of two or multiples of two ( $2 \cdot \text{NDIT}$ ) *frames* (due to the double-phase mode) each followed by detector readout and storage of the  $2 \cdot \text{NDIT}$  *frames*. A ZIMPOL measurement of one Stokes parameter requires a minimum (NDIT = 1) of one *exposure*, i.e. one *exposure* contains two *frames* or four *sub-frames*.
- For ZIMPOL imaging mode (I1), an *exposure* means the entity of one or more (NDIT) integrations (*frames*), each followed by detector readout and storage of the NDIT *frames*.

**Frame:** A *frame* is a single integration and readout of the data acquired during DIT seconds. Two *frames* in sequence in double-phase mode form the minimum of one ZIMPOL *exposure*. Each *frame* has a 'number'  $k = 1 \dots 2 \cdot \text{NDIT}$ .

**Sub-frame:** In general, a *sub-frame* is a part of a *frame*. For ZIMPOL, each *frame* consists of exactly two *sub-frames* independent of observing mode: The image data stored in all odd-numbered, exposed software pixel rows (*sub-frame*<sup>A</sup>), and that stored in all even-numbered pixel rows covered by the opaque stripe mask (*sub-frame*<sup>B</sup>). In the polarimetric modes P1, P2, P3, the demodulation fills the two *sub-frames* with the two complementary polarization images. The spatial field information in both *sub-frames* is the same, since they have been recorded through the same microlenses and exposed pixels. In imaging mode I1, where no demodulation takes place, the intensity image is stored only in the *sub-frame*<sup>A</sup> while the other *sub-frame*<sup>B</sup> remains empty.

### 5.18.2 Description of a ZIMPOL measurement in double-phase mode

To better understand and distinguish the different meanings of *exposure*, *frame* and *sub-frame*, a short explanation is given which is valid for all ZIMPOL double-phase mode measurements. Each frame (number  $k = 1 \dots 2 \cdot \text{NDIT}$ ) contains two sub-frames,  $i_k^A$  and  $i_k^B$ . Polarization modulation of the incoming light in combination with the demodulation performed on the CCD sensor during the integration time ensure that these two sub-frames represent an intensity image of two opposite Stokes polarization components (e.g.  $Q_+$  stored in  $i_k^A$ ,  $Q_-$  in  $i_k^B$ ). In double-phase mode, the demodulation phase is shifted by half a cycle between each consecutive pair of frames, effectively exchanging the assignments ( $Q_+$  stored in  $i_{k+1}^B$ ,  $Q_-$  in  $i_{k+1}^A$ ). In Figure 5.2a graphical explanation is given.

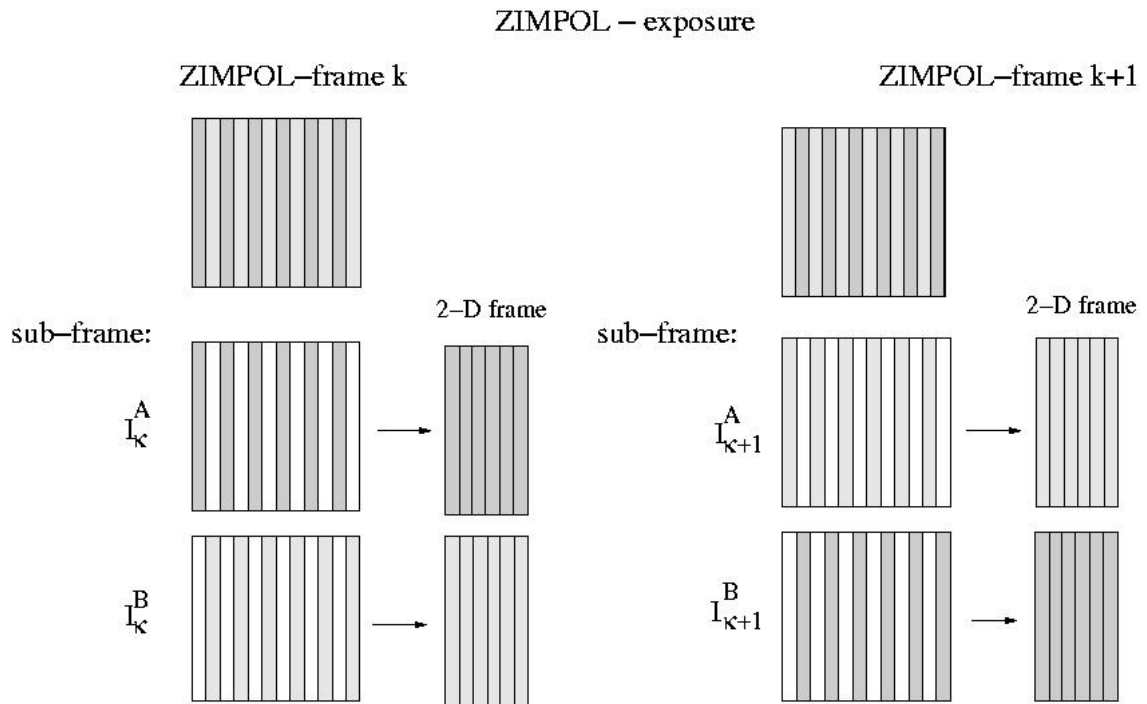


Figure 5.2: Schema of one single ZIMPOL *exposure* for the example of  $\text{NDIT}=1$ , leading to the output of two consecutive *frames* from each CCD. The left side is the  $k$ th ZIMPOL frame recorded at phase one of the double-phase mode, whereas the right side (frame  $k + 1$ ) has been recorded in the second phase. Each *frame* contains two interlaced *sub-frames*, storing two complementary polarization component images. Since the *frame* is square, extracting the two *sub-frames* yields two images with a 1:2 aspect ratio; a circle will be imaged as an ellipse). Dark grey means more intensity than light grey; white means that these columns contain no scientific data (but only noise).

When a cycle of NDIT frames is taken, the half-wave plate HWP2 is rotated by  $45^\circ$  (“HWP2 flip”), and the cycle of NDIT frames is repeated for the second HWP2 position. When the observations for both HWP2 positions are finished, an optional dithering is performed over NDITHER positions.

### 5.18.3 ZIMPOL CCD

The two chosen ZIMPOL CCDs are e2v 44-82 bi, in frame transfer mode (one CCD for each of the two cameras). One CCD has  $2k \times 4k$  pixels (hardware pixels of  $15 \times 15 \mu m$  size). The half of the CCD ( $2k \times 2k$ ) is covered by an opaque mask and is used as buffer storage only, the other half ( $2k \times 2k$ ) is exposed to light. The exposed part of the CCD is furthermore equipped with an opaque strip mask which alternately covers two rows of the CCD and leaves the next two rows open (e.g. row 1 and 2 are covered, 3 and 4 are open, 5 and 6 covered, 7 and 8 open, etc.). An on-chip (TBC)  $2 \times 2$  binning will reduce this to  $1k \times 1k$  software pixels ( $30 \times 30 \mu m$  size). Thus, from each camera  $1k \times 1k$  pixels are effectively read out.

The f/ number at the detector is f/221, leading to an image scale of  $\approx 0.117 \text{ mas}/\mu m$  a pixel scale of  $3.5 \text{ mas/pixel}$  (for  $1k \times 1k$  pixels).

The image scale in the sub-frames ( $1k \times 0.5k$ ) is doubled in one field direction. To make the image scale symmetric in both field directions, the images will be binned again during the data reduction to  $0.5k \times 0.5k$  final pixels of size  $60 \times 60 \mu m$  corresponding to an image scale of  $\approx 0.233 \text{ mas}/\mu m$  or a pixel scale of  $7 \text{ mas/pixel}$ . This corresponds to about half a resolution element at  $600 \text{ nm}$ , which is  $\lambda/D \approx 15.5 \text{ mas}$  (factor 1.1 oversampling compared to Nyquist criterion at  $600 \text{ nm}$ ).

The total field of view at the ZIMPOL focal plane is about  $8''$  diameter, whereas the entire detector covers only about  $3.5 \times 3.5''$ .

An extract of one ZIMPOL CCD can be seen in Figure 5.18.3. There, the boxes with the smallest sizes correspond to the  $15 \mu m$  sized hardware pixels. The always present on-chip (TBC)  $2 \times 2$  binning leads to the software pixels of  $30 \times 30 \mu m$  size which are read out. Later in the data reduction binning is applied anew, shown here with the largest filled box. A circle with the diameter of diffraction limited resolution is over-plotted to visualize the relations.

### 5.18.4 Dithering

Dithering is foreseen for all ZIMPOL observations. It will be implemented by keeping the telescope pointed at a fixed position on the sky and producing a series of movements of the tilt- and tip/tilt-mirrors in front of the ZIMPOL cameras providing a series of  $x, y$ -shifts of the field of view by a certain number of pixels.

The proposed idea is to enter a number of dithering positions (NDITHER) and the individual  $x, y$  offsets ( $\Delta x_i, \Delta y_i$ ) in the P2PP. The input NDITHER and the number of ( $\Delta x, \Delta y$ )-pairs are compared, and an error is signaled if they do not match. The offsets ( $\Delta x_i, \Delta y_i$ ) can be given in arcseconds or in pixel numbers (units to be selected from a menu bar). The numbers are calculated by the INS and the commands are given to the motors of the tilt- and tip/tilt mirrors. It shall also be possible to select predefined dithering positions, e.g. 9 (or 25) positions with the pointing at the center and the remaining 8 (or 24) positions aligned in a grid around the pointing position with offsets of e.g. 2 pixels. For each NDITHER position both HWP2 positions with NDIT frames each can be taken at the fixed position of FOV (telescope and tilt- and tip/tilt mirrors). The observation sequence is according to the “Observations modes and sequences” (RD4) the following:

NDIT frames  $\Rightarrow$  HWP2 flip ( $+45^\circ$ )  $\Rightarrow$  NDITHER dithering positions.

The following pseudo-code describes the procedure for a  $Q/I$  measurement (one exposure):

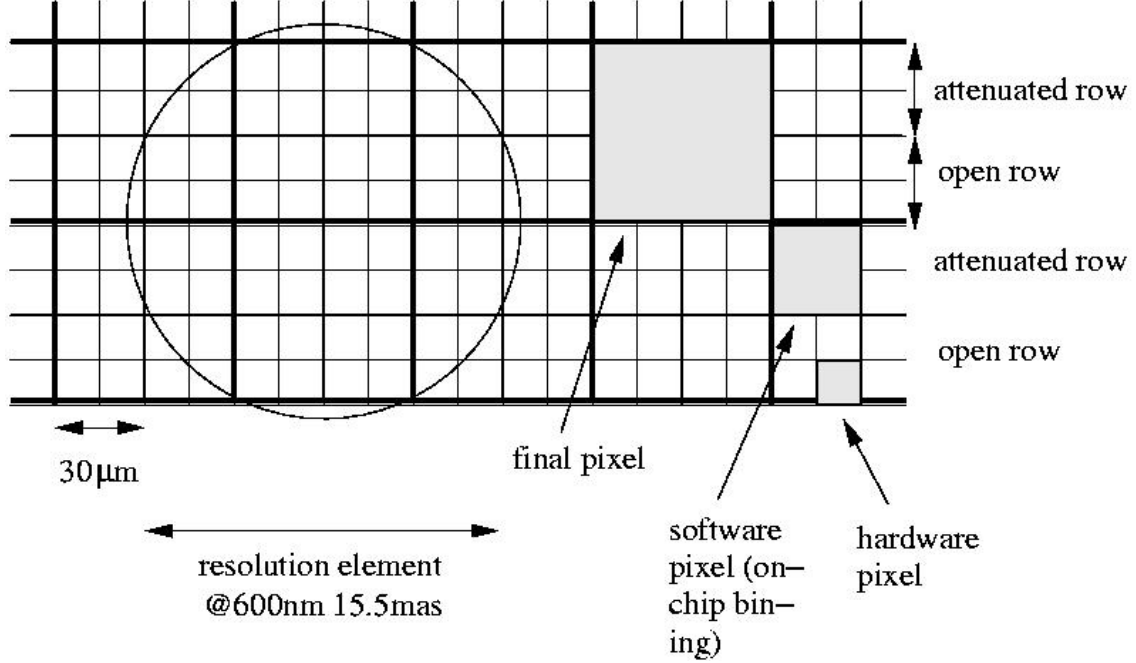


Figure 5.3: Detail of one ZIMPOL CCD with shown resolution element  $\lambda/D$ , the hardware pixel, the 2x2 binned software pixel and the final reduction pixel of 4x4 hardware pixels.

```

foriDither=0, NDITHER-1 do
  assume dithering position iDither
  setHWP2-offset angle to0
  foriDIT=0, NDIT-1 do
    take 1 frame with the first mode of the double-phase mode
    take 1 frame with the second mode of the double-phase mode
  end for
  setHWP2-offset angle to45
  foriDIT=0, NDIT-1 do
    take 1 frame with the first mode of the double-phase mode
    take 1 frame with the second mode of the double-phase mode
  end for
end for

```

### 5.18.5 Two-phase mode

In polarimetric detector modes, two more calibrations must be applied to the data after dark subtraction and intensity flat-fielding. As described in Section 5.18.2, each ZIMPOL frame  $k$  consists of two interlaced sub-frames  $i^A(k)$ ,  $i^B(k)$  that each store one polarization component, e.g.  $Q_+$ ,  $Q_-$ . From one frame to the next, the assignment of polarization components to sub-frames is reversed by switching the phase of the demodulation cycle from 0 to  $\pi$ , whereas the detector's fixed pattern noise (FPN) remains unchanged. This property is exploited to remove the fixed pattern noise:

$$Q^{(0)} = i_k^A - i_k^B = \frac{1}{2} ((+Q + FPN^A) - (-Q + FPN^B)), \quad (5.11)$$

$$Q^{(\pi)} = i_{k+1}^A - i_{k+1}^B = \frac{1}{2} ((-Q + FPN^A) - (+Q + FPN^B)), \quad (5.12)$$

$$Q = \frac{1}{2} \left( Q^{(0)} - Q^{(\pi)} \right). \quad (5.13)$$

The fixed pattern noise of a given pixel has been assumed to be constant there. In reality, it can depend on the flux of the pixel to some degree. If the pixel flux is different between the two polarization components, i.e. if  $Q \neq 0$ , some residual fixed pattern noise will survive this process. Therefore, it is imperative to keep the overall background polarization of the science image as low as possible. The ZIMPOL instrument uses a rotatable and tiltable glass plate to compensate the background polarization in real-time for this purpose.

## 5.19 Specific ZIMPOL detector calibration

We distinguish between two quite separate kinds of calibration: The detector calibration, which attempts to remove all detector imperfections from the read-out photocharge images and reconstruct the actual intensity distribution incident on the detectors (and is therefore locked to the grid of the detector pixels); and the Stokes vector calibration, which attempts to reconstruct the scientific Stokes vector coming in from the sky on the basis of the intensity distributions that reach the detector after propagation through the instrument (and is therefore locked to the coordinate system of the sky image).

### 5.19.1 Modulation / demodulation efficiency

The modulation / demodulation polarimetric efficiency of the ZIMPOL instrument (the  $Q \rightarrow Q$  element of its Mueller matrix) is dominated by effects of imperfect demodulation; therefore it is corrected pixel-wise as part of the detector calibration rather than as part of the Stokes vector calibration. The modulation / demodulation efficiency (MDE) is recorded under 100% polarized-flat illumination using two-phase mode. The  $Q/I$  science image is then divided by the resulting  $Q/I$  efficiency frame to remove those effects.

Therefore, the clean polarization image can be obtained as follows:

$$(Q/I)_{\text{clean}} = \frac{(Q/I)}{(Q/I)_{\text{MDE}}}. \quad (5.14)$$

## Chapter 6

# Installation Procedure and Troubleshooting

## 6.1 Installing the Pipeline

ESO pipelines can be installed via several methods, depending on your OS, most of which facilitate easy installation, upgrade and removal. Please see the ESO Data Reduction Pipelines and Workflow Systems page <https://www.eso.org/pipelines>.

## 6.2 Tips, tricks, and troubleshooting

### 6.2.1 My recipe run terminats with thousands of error messages...

Don't panic! Try to go through the log file produced by esorex and find the first ERROR signal. In many cases, this gives a hint what went wrong and what can be tried to correct the behaviour...

### 6.2.2 I still don't understand the error / it says that the 'actual error was lost'

Now panic! Better still, note that many parts of the pipeline are still untested and it's not unlikely you stumbled onto something that has never been tried before. Try to make a small package of data and a command line that can reproduce the error and contact us!

### 6.2.3 My distortion map or other peak-finding involving recipe doesn't produce an output and gives errors.

Recipes involving peak finding usually offer a `threshold` or `sigma` parameter in the command line. Some also offer `nsource` to pre-determine the number of sources to be found. Try playing with these in conjunction to looking at the images, in particular the peak intensity in relation to the background level, which should be `threshold` or `sigma` times apart. Note that in combination with a supplied `astrometry` as e.g. in `sph_ird_star_center`, the parameter value needed can be rather particular...so try also very large numbers here!



## Appendix A

# Quality Control Keywords

### A.1 Common

```
#
# Code define: SPH_COMMON_KEYWORD_QC_MEANMASTERFRAME
#
#   Code references:
#     - sph_master_frame.c
#
Parameter Name:    ESO QC MEANMASTER
Class:             header|qc-log
Context:           process
Type:              double
Value Format:       %.2f
Unit:              1
Comment Field:     Mean value of a master frame [1]
Description:       Mean value of a master frame

#
# Code define: SPH_COMMON_KEYWORD_QC_MEDIANMASTERFRAME
#
#   Code references:
#     - sph_master_frame.c
#
Parameter Name:    ESO QC MEDIANMASTER
Class:             header|qc-log
Context:           process
Type:              double
Value Format:       %.2f
Unit:              1
Comment Field:     Median value of a master frame[1]
Description:       Median value of a master frame

#
# Code define: SPH_COMMON_KEYWORD_QC_RMSMASTERFRAME
#
#   Code references:
#     - sph_master_frame.c
```



```
#
Parameter Name:    ESO QC RMSMASTER
Class:             header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             1
Comment Field:    RMS of a master frame[1]
Description:      RMS of a master frame

#
# Code define: SPH_COMMON_KEYWORD_QC_RON
#
#   Code references:
#   - sph_ird_gain_run.c
#   - sph_ifs_gain_run.c
#   - sph_gain_and_ron.c
#
Parameter Name:    ESO QC RON
Class:             header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU
Comment Field:    Determined read-out noise [ADU]
Description:      Determined read-out noise (ADU)

#
# Code define: SPH_COMMON_KEYWORD_QC_RON_RMS
#
#   Code references:
#   - sph_ird_gain_run.c
#   - sph_ifs_gain_run.c
#   - sph_gain_and_ron.c
#
Parameter Name:    ESO QC RON RMS
Class:             header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU
Comment Field:    RMS of determined read-outnoise [ADU]
Description:      RMS of determined read-out noise (ADU)

#
# Code define: SPH_COMMON_KEYWORD_QC_GAIN
#
#   Code references:
#   - sph_ird_gain_run.c
#   - sph_ifs_gain_run.c
#   - sph_gain_and_ron.c
#
Parameter Name:    ESO QC GAIN
Class:             header|qc-log
```



Context: process  
Type: double  
Value Format: %.2f  
Unit: e-/ADU  
Comment Field: Determined gain [e-/ADU]  
Description: Determined gain (e-/ADU)

```
#  
# Code define: SPH_COMMON_KEYWORD_QC_GAIN_RMS  
#  
# Code references:  
# - sph_ird_gain_run.c  
# - sph_ifs_gain_run.c  
# - sph_gain_and_ron.c  
#
```

Parameter Name: ESO QC GAIN RMS  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: e-/ADU  
Comment Field: Determined RMS of gain [e-/ADU]  
Description: Determined RMS of gain (e-/ADU)

```
#  
# Code define: SPH_COMMON_KEYWORD_QC_MEAN_DOUBLEIMAGE_IFRAME  
#  
# Code references:  
# - sph_double_image.c  
#
```

Parameter Name: ESO QC DOUBLE IMAGE IFRAME MEAN  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: Mean value of an intensity double image (ZIMPOL)[ADU]  
Description: Mean value of an intensity double image (ZIMPOL)

```
#  
# Code define: SPH_COMMON_KEYWORD_QC_MEDIAN_DOUBLEIMAGE_IFRAME  
#  
# Code references:  
# - sph_double_image.c  
#
```

Parameter Name: ESO QC DOUBLE IMAGE IFRAME MEDIAN  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: Median value of an intensity double image (ZIMPOL)[ADU]  
Description: Median value of an intensity double image (ZIMPOL)



```
#
# Code define: SPH_COMMON_KEYWORD_QC_RMS_DOUBLEIMAGE_IFRAME
#
#   Code references:
#     - sph_double_image.c
#
Parameter Name:   ESO QC DOUBLE IMAGE IFRAME RMS
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU
Comment Field:    RMS of an intensity double image (ZIMPOL) [ADU]
Description:      RMS of an intensity double image (ZIMPOL)

#
# Code define: SPH_COMMON_KEYWORD_QC_MEAN_DOUBLEIMAGE_PFRAME
#
#   Code references:
#     - sph_double_image.c
#
Parameter Name:   ESO QC DOUBLE IMAGE PFRAME MEAN
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             1
Comment Field:    Mean value of a polarization degree double image (ZIMPOL) [1]
Description:      Mean value of a polarization degree double image (ZIMPOL)

#
# Code define: SPH_COMMON_KEYWORD_QC_MEDIAN_DOUBLEIMAGE_PFRAME
#
#   Code references:
#     - sph_double_image.c
#
Parameter Name:   ESO QC DOUBLE IMAGE PFRAME MEDIAN
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             1
Comment Field:    Median value of a polarization degree double image (ZIMPOL) [1]
Description:      Median value of a polarization degree double image (ZIMPOL)

#
# Code define: SPH_COMMON_KEYWORD_QC_RMS_DOUBLEIMAGE_PFRAME
#
#   Code references:
#     - sph_double_image.c
#
Parameter Name:   ESO QC DOUBLE IMAGE PFRAME RMS
Class:            header|qc-log
Context:          process
```



Type: double  
Value Format: %.2f  
Unit: 1  
Comment Field: RMS of a polarization degree double image (ZIMPOL)[1]  
Description: RMS of a polarization degree double image (ZIMPOL)

```
#  
# Code define: SPH_COMMON_KEYWORD_QC_MEAN_TRIPLEIMAGE_IFRAME  
#  
# Code references:  
#   - sph_triple_image.c  
#
```

Parameter Name: ESO QC TRIPLE IMAGE IFRAME MEAN  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: Mean value of an intensity triple image (ZIMPOL)[ADU]  
Description: Mean value of an intensity triple image (ZIMPOL)

```
#  
# Code define: SPH_COMMON_KEYWORD_QC_MEDIAN_TRIPLEIMAGE_IFRAME  
#  
# Code references:  
#   - sph_triple_image.c  
#
```

Parameter Name: ESO QC TRIPLE IMAGE IFRAME MEDIAN  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: Median value of an intensity triple image (ZIMPOL)[ADU]  
Description: Median value of an intensity triple image (ZIMPOL)

```
#  
# Code define: SPH_COMMON_KEYWORD_QC_RMS_TRIPLEIMAGE_IFRAME  
#  
# Code references:  
#   - sph_triple_image.c  
#
```

Parameter Name: ESO QC TRIPLE IMAGE IFRAME RMS  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: RMS of an intensity triple image (ZIMPOL)[ADU]  
Description: RMS of an intensity triple image (ZIMPOL)

```
#  
# Code define: SPH_COMMON_KEYWORD_QC_MEAN_TRIPLEIMAGE_QFRAME  
#
```



```
# Code references:
#   - sph_triple_image.c
#
Parameter Name:   ESO QC TRIPLE IMAGE QFRAME MEAN
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:            1
Comment Field:    Mean value of a Q triple image (ZIMPOL)[1]
Description:      Mean value of a Q triple image (ZIMPOL)

#
# Code define: SPH_COMMON_KEYWORD_QC_MEDIAN_TRIPLEIMAGE_QFRAME
#
# Code references:
#   - sph_triple_image.c
#
Parameter Name:   ESO QC TRIPLE IMAGE QFRAME MEDIAN
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:            1
Comment Field:    Median value of a Q triple image (ZIMPOL)[1]
Description:      Median value of a Q triple image (ZIMPOL)

#
# Code define: SPH_COMMON_KEYWORD_QC_RMS_TRIPLEIMAGE_QFRAME
#
# Code references:
#   - sph_triple_image.c
#
Parameter Name:   ESO QC TRIPLE IMAGE QFRAME RMS
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:            1
Comment Field:    RMS of a Q triple image (ZIMPOL)[1]
Description:      RMS of a Q triple image (ZIMPOL)

#
# Code define: SPH_COMMON_KEYWORD_QC_MEAN_TRIPLEIMAGE_UFRAME
#
# Code references:
#   - sph_triple_image.c
#
Parameter Name:   ESO QC TRIPLE IMAGE UFRAME MEAN
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:            1
```



Comment Field: Mean value of a U triple image (ZIMPOL)[1]

Description: Mean value of a U triple image (ZIMPOL)

#

# Code define: SPH\_COMMON\_KEYWORD\_QC\_MEDIAN\_TRIPLEIMAGE\_UFRAME

#

# Code references:

# - sph\_triple\_image.c

#

Parameter Name: ESO QC TRIPLE IMAGE UFRAME MEDIAN

Class: header|qc-log

Context: process

Type: double

Value Format: %.2f

Unit: 1

Comment Field: Median value of a U triple image (ZIMPOL)[1]

Description: Median value of a U triple image (ZIMPOL)

#

# Code define: SPH\_COMMON\_KEYWORD\_QC\_RMS\_TRIPLEIMAGE\_UFRAME

#

# Code references:

# - sph\_triple\_image.c

#

Parameter Name: ESO QC TRIPLE IMAGE UFRAME RMS

Class: header|qc-log

Context: process

Type: double

Value Format: %.2f

Unit: 1

Comment Field: RMS a U triple image (ZIMPOL)[1]

Description: RMS of a U triple image (ZIMPOL)

#

# Code define: SPH\_COMMON\_KEYWORD\_QC\_MEAN\_QUADIMAGE\_ZERO\_ODD

#

# Code references:

# - sph\_quad\_image.c

#

Parameter Name: ESO QC QUAD IMAGE ZERO ODD MEAN

Class: header|qc-log

Context: process

Type: double

Value Format: %.2f

Unit: ADU

Comment Field: Mean value of a zero-odd quadimage [ADU]

Description: Mean value of a zero-odd quadimage (ZIMPOL)

#

# Code define: SPH\_COMMON\_KEYWORD\_QC\_MEDIAN\_QUADIMAGE\_ZERO\_ODD

#

# Code references:

# - sph\_quad\_image.c

#



Parameter Name: ESO QC QUAD IMAGE ZERO ODD MEDIAN  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: Median value of a zero-odd quadimage [ADU]  
Description: Median value of a zero-odd quadimage (ZIMPOL)

```
#  
# Code define: SPH_COMMON_KEYWORD_QC_RMS_QUADIMAGE_ZERO_ODD  
#  
# Code references:  
#   - sph_quad_image.c  
#
```

Parameter Name: ESO QC QUAD IMAGE ZERO ODD RMS  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: RMS of a zero-odd quadimage [ADU]  
Description: RMS of a zero-odd quadimage (ZIMPOL)

```
#  
# Code define: SPH_COMMON_KEYWORD_QC_MEAN_QUADIMAGE_ZERO_EVEN  
#  
# Code references:  
#   - sph_quad_image.c  
#
```

Parameter Name: ESO QC QUAD IMAGE ZERO EVEN MEAN  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: Mean value of a zero-even quadimage [ADU]  
Description: Mean value of a zero-even quadimage (ZIMPOL)

```
#  
# Code define: SPH_COMMON_KEYWORD_QC_MEDIAN_QUADIMAGE_ZERO_EVEN  
#  
# Code references:  
#   - sph_quad_image.c  
#
```

Parameter Name: ESO QC QUAD IMAGE ZERO EVEN MEDIAN  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: Median value of a zero-even quadimage [ADU]  
Description: Median value of a zero-even quadimage (ZIMPOL)



```
#
# Code define: SPH_COMMON_KEYWORD_QC_RMS_QUADIMAGE_ZERO_EVEN
#
#   Code references:
#     - sph_quad_image.c
#
Parameter Name:   ESO QC QUAD IMAGE ZERO EVEN RMS
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU
Comment Field:    RMS of a zero-even quadimage [ADU]
Description:      RMS of a zero-even quadimage (ZIMPOL)

#
# Code define: SPH_COMMON_KEYWORD_QC_MEAN_QUADIMAGE_PI_ODD
#
#   Code references:
#     - sph_quad_image.c
#
Parameter Name:   ESO QC QUAD IMAGE PI ODD MEAN
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU
Comment Field:    Mean value of a pi-odd quadimage [ADU]
Description:      Mean value of a pi-odd quadimage (ZIMPOL)

#
# Code define: SPH_COMMON_KEYWORD_QC_MEDIAN_QUADIMAGE_PI_ODD
#
#   Code references:
#     - sph_quad_image.c
#
Parameter Name:   ESO QC QUAD IMAGE PI ODD MEDIAN
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU
Comment Field:    Median value of a pi-odd quadimage [ADU]
Description:      Median value of a pi-odd quadimage (ZIMPOL)

#
# Code define: SPH_COMMON_KEYWORD_QC_RMS_QUADIMAGE_PI_ODD
#
#   Code references:
#     - sph_quad_image.c
#
Parameter Name:   ESO QC QUAD IMAGE PI ODD RMS
Class:            header|qc-log
Context:          process
```



Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: RMS of a pi-odd quadimage [ADU]  
Description: RMS of a pi-odd quadimage (ZIMPOL)

```
#  
# Code define: SPH_COMMON_KEYWORD_QC_MEAN_QUADIMAGE_PI_EVEN  
#  
# Code references:  
# - sph_quad_image.c  
#
```

Parameter Name: ESO QC QUAD IMAGE PI EVEN MEAN  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: Mean value of a pi-even quadimage [ADU]  
Description: Mean value of a pi-even quadimage (ZIMPOL)

```
#  
# Code define: SPH_COMMON_KEYWORD_QC_MEDIAN_QUADIMAGE_PI_EVEN  
#  
# Code references:  
# - sph_quad_image.c  
#
```

Parameter Name: ESO QC QUAD IMAGE PI EVEN MEDIAN  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: Median value of a pi-even quadimage [ADU]  
Description: Median value of a pi-even quadimage (ZIMPOL)

```
#  
# Code define: SPH_COMMON_KEYWORD_QC_RMS_QUADIMAGE_PI_EVEN  
#  
# Code references:  
# - sph_quad_image.c  
#
```

Parameter Name: ESO QC QUAD IMAGE PI EVEN RMS  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: RMS of a pi-evn quadimage [ADU]  
Description: RMS of a pi-even quadimage (ZIMPOL)

```
#  
# Code define: SPH_COMMON_KEYWORD_DARK_MEAN_RON  
#
```



```
# Code references:
#   - sph_ird_master_dark_run.c
#   - sph_ifs_master_dark_run.c
#
Parameter Name:   ESO QC MEAN RON
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU
Comment Field:    mean dark RON estimate [ADU]
Description:      Mean dark RON estimate (ADU)

#
# Code define: SPH_COMMON_KEYWORD_INSBG_MEAN_COUNT
#
# Code references:
#   - sph_ird_sky_bg_run.c
#   - sph_ird_ins_bg_run.c
#
Parameter Name:   ESO QC INSBG MEAN
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU
Comment Field:    mean instrument background count [ADU]
Description:      Mean instrument background count (ADU)

#
# Code define: SPH_COMMON_KEYWORD_INSBG_RMS_COUNT
#
# Code references:
#   - sph_ird_ins_bg_run.c
#
Parameter Name:   ESO QC INSBG RMS
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU
Comment Field:    mean instrument background RMS [ADU]
Description:      Mean instrument background count (ADU)

#
# Code define: SPH_COMMON_KEYWORD_SKYBG_MEAN_COUNT
#
#
Parameter Name:   ESO QC SKYBG MEAN
Class:            header|qc-log
Context:          process
Type:             string
Value Format:      %30s
Unit:             ADU
```



Comment Field: mean sky background count [ADU]  
Description: Mean sky background count (ADU)

```
#
# Code define: SPH_COMMON_KEYWORD_SKYBG_RMS_COUNT
#
```

```
# Code references:
# - sph_ird_sky_bg_run.c
#
```

Parameter Name: ESO QC SKYBG RMS  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: mean sky background RMS [ADU]  
Description: Mean sky background count (ADU)

```
#
# Code define: SPH_COMMON_KEYWORD_NUMBER_HOTPIXELS
#
```

```
# Code references:
# - sph_ird_sky_bg_run.c
# - sph_ird_ins_bg_run.c
# - sph_ird_master_dark_run.c
# - sph_ifs_master_dark_run.c
#
```

Parameter Name: ESO QC NUM HOTPIXELS  
Class: header|qc-log  
Context: process  
Type: int  
Value Format: %d  
Unit: 1  
Comment Field: No. of identified hot pixels [1]  
Description: Number of identified hot pixels

```
#
# Code define: SPH_COMMON_KEYWORD_FLAT_FPN
#
```

```
# Code references:
# - sph_ird_instrument_flat_run.c
# - sph_ird_tff_run.c
# - sph_ifs_instrument_flat_run.c
# - sph_ifs_master_detector_flat_run.c
#
```

Parameter Name: ESO QC FPN  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: 1  
Comment Field: Fixed pattern noise [1]  
Description: Fixed pattern noise



```
#
# Code define: SPH_COMMON_KEYWORD_FLAT_RMS
#
#   Code references:
#     - sph_ird_instrument_flat_run.c
#     - sph_ird_tff_run.c
#
Parameter Name:   ESO QC RMS
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             1
Comment Field:    Root mean squared [1]
Description:      Root mean squared

#
# Code define: SPH_COMMON_KEYWORD_FLAT_NONLIN_FACTOR
#
#   Code references:
#     - sph_ird_instrument_flat_run.c
#     - sph_ird_tff_run.c
#     - sph_ifs_instrument_flat_run.c
#     - sph_ifs_master_detector_flat_run.c
#
Parameter Name:   ESO QC FLAT NONLINEARITY
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             1
Comment Field:    nonlinearity coefficient [1]
Description:      nonlinearity coefficient

#
# Code define: SPH_COMMON_KEYWORD_FLAT_MEAN_COUNT
#
#   Code references:
#     - sph_ird_instrument_flat_run.c
#     - sph_ird_tff_run.c
#     - sph_ifs_instrument_flat_run.c
#     - sph_ifs_master_detector_flat_run.c
#
Parameter Name:   ESO QC FLAT MEAN
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU
Comment Field:    Mean counts in flat field [ADU]
Description:      Mean counts in flat field

#
# Code define: SPH_COMMON_KEYWORD_NUMBER_BADPIXELS
```



```
#
# Code references:
#   - sph_ird_instrument_flat_run.c
#   - sph_ird_tff_run.c
#   - sph_zpl_intensity_flat_run.c
#   - sph_ifs_instrument_flat_run.c
#   - sph_ifs_master_detector_flat_run.c
#   - sph_gain_and_ron.c
#
Parameter Name:   ESO QC NUM BADPIXELS
Class:            header|qc-log
Context:          process
Type:             int
Value Format:      %d
Unit:             1
Comment Field:    No. of identified bad pixels [1]
Description:      number of identified bad pixels

#
# Code define: SPH_COMMON_KEYWORD_FLAT_LAMP_FLUX
#
# Code references:
#   - sph_ifs_instrument_flat_run.c
#   - sph_ifs_master_detector_flat_run.c
#   - sph_ifs_wave_calib_run.c
#
Parameter Name:   ESO QC LAMP FLUX AVG
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU/s
Comment Field:    Lamp flux in single frame [ADU/s]
Description:      Lamp flux (counts/s in single frame)

#
# Code define: SPH_COMMON_KEYWORD_FLAT_LAMP_COUNTS
#
# Code references:
#   - sph_ifs_instrument_flat_run.c
#
Parameter Name:   ESO QC LAMP ADU AVG
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU
Comment Field:    Lamp counts in single frame [ADU]
Description:      Lamp ADU (counts in single frame)

#
# Code define: SPH_COMMON_KEYWORD_FLAT_LAMP_FLUX_STDEV
#
# Code references:
```



```
# - sph_ifs_instrument_flat_run.c
# - sph_ifs_master_detector_flat_run.c
# - sph_ifs_wave_calib_run.c
#
Parameter Name:   ESO QC LAMP FLUX VARIANCE
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU/s
Comment Field:    Lamp flux stdev in single frame [ADU/s]
Description:      Lamp flux stdev (counts/s in single frame)

#
# Code define: SPH_COMMON_KEYWORD_MEDIAN_RESOLVING_POWER
#
#   Code references:
#   - sph_ifs_wave_calib_run.c
#
Parameter Name:   ESO QC MEDIAN RESOLVING POWER
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             1
Comment Field:    median resolving power [1]
Description:      median resolving power

#
# Code define: SPH_COMMON_KEYWORD_MEDIAN_DISPERSION
#
#   Code references:
#   - sph_ifs_wave_calib_run.c
#
Parameter Name:   ESO QC MEDIAN DISPERSION
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             micron/px
Comment Field:    median dispersion [micron/px]
Description:      median value of dispersion

#
# Code define: SPH_COMMON_KEYWORD_MEDIAN_MAXWAVEL
#
#   Code references:
#   - sph_ifs_wave_calib_run.c
#
Parameter Name:   ESO QC MEDIAN MAX WAVEL
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
```



Unit: micron  
Comment Field: median value of longest wavelength [micron]  
Description: median value of longest wavelength

#  
# Code define: SPH\_COMMON\_KEYWORD\_QC\_WAVE\_NDISP

#  
# Code references:  
# - sph\_ifs\_wave\_calib\_run.c  
#

Parameter Name: ESO QC NUM OUT OF DISP  
Class: header|qc-log  
Context: process  
Type: int  
Value Format: %d  
Unit: 1  
Comment Field: no. of wavelengths out of 1 dispersion [1]  
Description: no. of wavelengths out of 1 dispersion

#  
# Code define: SPH\_COMMON\_KEYWORD\_QC\_WAVE\_BADSPEC

#  
# Code references:  
# - sph\_ifs\_wave\_calib\_run.c  
#

Parameter Name: ESO QC BAD SPECTRA  
Class: header|qc-log  
Context: process  
Type: int  
Value Format: %d  
Unit: 1  
Comment Field: no. of bad spectra [1]  
Description: no. of bad spectra

#  
# Code define: SPH\_COMMON\_KEYWORD\_DISTMAP\_NREMOVED

#  
# Code references:  
# - sph\_distortion\_model.c  
#

Parameter Name: ESO QC DISTMAP NREMOVED  
Class: header|qc-log  
Context: process  
Type: int  
Value Format: %d  
Unit: 1  
Comment Field: no. of points removed from distortion map [1]  
Description: no. of points removed from distortion map

#  
# Code define: SPH\_COMMON\_KEYWORD\_DISTMAP\_PIXSCALE

#  
# Code references:  
# - sph\_distortion\_model.c

```
#
Parameter Name:      ESO QC DISTMAP PIXSCALE
Class:               header|qc-log
Context:             process
Type:                double
Value Format:         %.2f
Unit:                1
Comment Field:       relative distortion map pixel scale [1]
Description:         distortion map pixel scale

#
# Code define: SPH_COMMON_KEYWORD_QC_NUMBER_BADPIXELS_ZPLEXP_ZERO_ODD
#
#   Code references:
#     - sph_zpl_intensity_flat_run.c
#
Parameter Name:      ESO QC ZPL EXP ZERO ODD NUMBER BADPIXELS
Class:               header|qc-log
Context:             process
Type:                double
Value Format:         %.2f
Unit:                1
Comment Field:       number of bad pixels[1]
Description:         number of bad pixels

#
# Code define: SPH_COMMON_KEYWORD_QC_NUMBER_BADPIXELS_ZPLEXP_ZERO_EVEN
#
#   Code references:
#     - sph_zpl_intensity_flat_run.c
#
Parameter Name:      ESO QC ZPL EXP ZERO EVEN NUMBER BADPIXELS
Class:               header|qc-log
Context:             process
Type:                double
Value Format:         %.2f
Unit:                1
Comment Field:       number of bad pixels [1]
Description:         number of bad pixels

#
# Code define: SPH_COMMON_KEYWORD_QC_NUMBER_BADPIXELS_ZPLEXP_PI_ODD
#
#   Code references:
#     - sph_zpl_intensity_flat_run.c
#
Parameter Name:      ESO QC ZPL EXP PI ODD NUMBER BADPIXELS
Class:               header|qc-log
Context:             process
Type:                double
Value Format:         %.2f
Unit:                1
Comment Field:       number of bad pixels [1]
Description:         number of bad pixels
```



```
#
# Code define: SPH_COMMON_KEYWORD_QC_NUMBER_BADPIXELS_ZPLEXP_PI_EVEN
#
#   Code references:
#     - sph_zpl_intensity_flat_run.c
#
Parameter Name:   ESO QC ZPL EXP PI EVEN NUMBER BADPIXELS
Class:           header|qc-log
Context:         process
Type:            double
Value Format:     %.2f
Unit:            1
Comment Field:   number of bad pixels [1]
Description:     number of bad pixels

#
# Code define: SPH_COMMON_KEYWORD_QC_NUMBER_BADPIXELS_QUAD_IMAGE_ZERO_ODD
#
#   Code references:
#     - sph_zpl_intensity_flat_run.c
#     - sph_zpl_master_bias_run.c
#     - sph_zpl_master_dark_run.c
#     - sph_quad_image.c
#
Parameter Name:   ESO QC QUAD IMAGE ZERO ODD NUMBER BADPIXELS
Class:           header|qc-log
Context:         process
Type:            long
Value Format:     %.2f
Unit:            1
Comment Field:   number of bad pixels [1]
Description:     number of bad pixels

#
# Code define: SPH_COMMON_KEYWORD_QC_NUMBER_BADPIXELS_QUAD_IMAGE_ZERO_EVEN
#
#   Code references:
#     - sph_zpl_intensity_flat_run.c
#     - sph_zpl_master_bias_run.c
#     - sph_zpl_master_dark_run.c
#     - sph_quad_image.c
#
Parameter Name:   ESO QC QUAD IMAGE ZERO EVEN NUMBER BADPIXELS
Class:           header|qc-log
Context:         process
Type:            long
Value Format:     %.2f
Unit:            1
Comment Field:   number of bad pixels [1]
Description:     number of bad pixels

#
# Code define: SPH_COMMON_KEYWORD_QC_NUMBER_BADPIXELS_QUAD_IMAGE_PI_ODD
```



```
#
# Code references:
#   - sph_zpl_intensity_flat_run.c
#   - sph_zpl_master_bias_run.c
#   - sph_zpl_master_dark_run.c
#   - sph_quad_image.c
#
Parameter Name:    ESO QC QUAD IMAGE PI ODD NUMBER BADPIXELS
Class:             header|qc-log
Context:           process
Type:              long
Value Format:       %.2f
Unit:              1
Comment Field:     number of bad pixels [1]
Description:       number of bad pixels

#
# Code define: SPH_COMMON_KEYWORD_QC_NUMBER_BADPIXELS_QUAD_IMAGE_PI_EVEN
#
# Code references:
#   - sph_zpl_intensity_flat_run.c
#   - sph_zpl_master_bias_run.c
#   - sph_zpl_master_dark_run.c
#   - sph_quad_image.c
#
Parameter Name:    ESO QC QUAD IMAGE PI EVEN NUMBER BADPIXELS
Class:             header|qc-log
Context:           process
Type:              long
Value Format:       %.2f
Unit:              1
Comment Field:     number of bad pixels [1]
Description:       number of bad pixels

#
# Code define: SPH_COMMON_KEYWORD_QC_NUMBER_BADPIXELS_ZPLEXP_IMG_ODD
#
# Code references:
#   - sph_zpl_intensity_flat_imaging_run.c
#
Parameter Name:    ESO QC ZPL EXP IMAGING ODD NUMBER BADPIXELS
Class:             header|qc-log
Context:           process
Type:              double
Value Format:       %.2f
Unit:              1
Comment Field:     number of bad pixels [1]
Description:       number of bad pixels

#
# Code define: SPH_COMMON_KEYWORD_QC_NUMBER_BADPIXELS_ZPLEXP_IMG_EVEN
#
# Code references:
#   - sph_zpl_intensity_flat_imaging_run.c
```



```
#
Parameter Name:    ESO QC ZPL EXP IMAGING EVEN NUMBER BADPIXELS
Class:             header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             1
Comment Field:    number of bad pixels [1]
Description:      number of bad pixels

#
# Code define: SPH_COMMON_KEYWORD_QC_NUMBER_BADPIXELS_DOUBLE_IMAGE_ODD
#
#   Code references:
#   - sph_zpl_intensity_flat_imaging_run.c
#   - sph_double_image.c
#
Parameter Name:    ESO QC DOUBLE IMAGE ODD-I NUMBER BADPIXELS
Class:             header|qc-log
Context:          process
Type:             long
Value Format:      %.2f
Unit:             1
Comment Field:    number of bad pixels [1]
Description:      number of bad pixels

#
# Code define: SPH_COMMON_KEYWORD_QC_NUMBER_BADPIXELS_DOUBLE_IMAGE_EVEN
#
#   Code references:
#   - sph_zpl_intensity_flat_imaging_run.c
#   - sph_double_image.c
#
Parameter Name:    ESO QC DOUBLE IMAGE EVEN-P NUMBER BADPIXELS
Class:             header|qc-log
Context:          process
Type:             long
Value Format:      %.2f
Unit:             1
Comment Field:    number of bad pixels [1]
Description:      number of bad pixels

#
# Code define: SPH_COMMON_KEYWORD_QC_LOCI_NRINGS
#
#   Code references:
#   - sph_ird_loci_run.c
#
Parameter Name:    ESO QC LOCI NRINGS
Class:             header|qc-log
Context:          process
Type:             int
Value Format:      %d
Unit:             1
```



Comment Field: number of rings used by LOCI [1]

Description: number of rings used by LOCI

#

# Code define: SPH\_COMMON\_KEYWORD\_QC\_LOCI\_NSUBSECTIONS

#

# Code references:

# - sph\_ird\_loci\_run.c

#

Parameter Name: ESO QC LOCI NSECT

Class: header|qc-log

Context: process

Type: int

Value Format: %d

Unit: 1

Comment Field: number of sub-sections used by LOCI [1]

Description: number of sub-sections used by LOCI

#

# Code define: SPH\_COMMON\_KEYWORD\_QC\_LOCI\_NBADSECTIONS

#

# Code references:

# - sph\_ird\_loci\_run.c

#

Parameter Name: ESO QC LOCI NSECT BAD

Class: header|qc-log

Context: process

Type: int

Value Format: %d

Unit: 1

Comment Field: number of bad sub-sections [1]

Description: number of bad sub-sections

#

# Code define: SPH\_STREHL\_QC\_STREHL

#

#

Parameter Name: ESO QC STREHL

Class: header|qc-log

Context: process

Type: string

Value Format: %30s

Unit: 1

Comment Field: Strehl ratio measured on brightest source in field

Description: Strehl ratio measured on brightest source in field

#

# Code define: SPH\_STREHL\_QC\_STREHL\_ERR

#

#

Parameter Name: ESO QC STREHL ERROR

Class: header|qc-log

Context: process

Type: string

```

Value Format:      %30s
Unit:             1
Comment Field:    Error of Strehl ratio measured on brightest source in field
Description:      Error of Strehl ratio measured on brightest source in field

#
# Code define: SPH_STREHL_QC_STREHL_POSX
#
#
Parameter Name:   ESO QC STREHL POSX
Class:            header|qc-log
Context:          process
Type:             string
Value Format:      %30s
Unit:             1
Comment Field:    X coordinate of position of source used for Strehl measurement
Description:      X coordinate of position of source used for Strehl measurement

#
# Code define: SPH_STREHL_QC_STREHL_POSY
#
#
Parameter Name:   ESO QC STREHL POSY
Class:            header|qc-log
Context:          process
Type:             string
Value Format:      %30s
Unit:             1
Comment Field:    Y coordinate of position of source used for Strehl measurement
Description:      Y coordinate of position of source used for Strehl measurement

#
# Code define: SPH_STREHL_QC_STREHL_SIGMA
#
#
Parameter Name:   ESO QC STREHL SIGMA
Class:            header|qc-log
Context:          process
Type:             string
Value Format:      %30s
Unit:             1
Comment Field:    Sigma of Strehl measurement (?)
Description:      Sigma of Strehl measurement

#
# Code define: SPH_STREHL_QC_STREHL_FLUX
#
#
Parameter Name:   ESO QC STREHL FLUX
Class:            header|qc-log
Context:          process
Type:             string
Value Format:      %30s
Unit:             ADU

```



Comment Field: Flux measured in aperture for Strehl measurement [ADU]

Description: Flux measured in aperture for Strehl measurement

#

# Code define: SPH\_STREHL\_QC\_STREHL\_PEAK

#

#

Parameter Name: ESO QC STREHL PEAK

Class: header|qc-log

Context: process

Type: string

Value Format: %30s

Unit: ADU

Comment Field: Peak intensity in aperture used for Strehl measurement [ADU]

Description: Peak intensity in aperture used for Strehl measurement

#

# Code define: SPH\_STREHL\_QC\_STREHL\_BKG

#

#

Parameter Name: ESO QC STREHL BACKGROUND

Class: header|qc-log

Context: process

Type: string

Value Format: %30s

Unit: ADU

Comment Field: Background flux per pixel in aperture used for Strehl measurement [ADU]

Description: Background flux per pixel in aperture used for Strehl measurement

#

# Code define: SPH\_STREHL\_QC\_STREHL\_BKGNOISE

#

#

Parameter Name: ESO QC STREHL BACKGROUND NOISE

Class: header|qc-log

Context: process

Type: string

Value Format: %30s

Unit: ADU

Comment Field: Noise of background flux per pixel in aperture used for Strehl measurement [ADU]

Description: Noise of background flux per pixel in aperture used for Strehl measurement

## A.2 IRDIS

#

# Code define: SPH\_IRD\_KEYWORD\_WAVECALIB\_NGOODLINES

#

# Code references:

# - sph\_ird\_wave\_calib\_run.c

#

Parameter Name: ESO QC WAVECAL NGOODCOLUMNS



Class: header|qc-log  
 Context: process  
 Type: int  
 Value Format: %d  
 Unit: 1  
 Comment Field: Number of good spectral regions / Columns [1]  
 Description: Number of good columns

#  
 # Code define: SPH\_IRD\_KEYWORD\_WAVECALIB\_NBADLINES

#  
 # Code references:  
 # - sph\_ird\_wave\_calib\_run.c  
 #

Parameter Name: ESO QC WAVECAL NBADCOLUMNS  
 Class: header|qc-log  
 Context: process  
 Type: int  
 Value Format: %d  
 Unit: 1  
 Comment Field: Number of bad spectral regions / columns [1]  
 Description:

#  
 # Code define: SPH\_IRD\_KEYWORD\_WAVECALIB\_NNOFITLINES

#  
 # Code references:  
 # - sph\_ird\_wave\_calib\_run.c  
 #

Parameter Name: ESO QC WAVECAL NNOFITCOLUMNS  
 Class: header|qc-log  
 Context: process  
 Type: int  
 Value Format: %d  
 Unit: 1  
 Comment Field: Number of spectral regions/columns without fit [1]  
 Description:

#  
 # Code define: SPH\_IRD\_KEYWORD\_WAVECALIB\_YO\_MEAN

#  
 # Code references:  
 # - sph\_ird\_wave\_calib\_run.c  
 #

Parameter Name: ESO QC WAVECAL YO MEAN  
 Class: header|qc-log  
 Context: process  
 Type: double  
 Value Format: %.2f  
 Unit: micron  
 Comment Field: Mean minimum wavelength [micron]  
 Description:

#  
 # Code define: SPH\_IRD\_KEYWORD\_WAVECALIB\_YO\_RMS

#  
 # Code references:



```
# - sph_ird_wave_calib_run.c
#
Parameter Name:    ESO QC WAVECAL YO RMS
Class:             header|qc-log
Context:           process
Type:              double
Value Format:       %.2f
Unit:              micron
Comment Field:     RMS of minimum wavelength [micron]
Description:
#
# Code define: SPH_IRD_KEYWORD_WAVECALIB_C1_MEAN
#
# Code references:
# - sph_ird_wave_calib_run.c
#
Parameter Name:    ESO QC WAVECAL C1 MEAN
Class:             header|qc-log
Context:           process
Type:              double
Value Format:       %.2f
Unit:              micron/pix
Comment Field:     Mean slope of wavelength solution [micron/pix]
Description:
#
# Code define: SPH_IRD_KEYWORD_WAVECALIB_C1_RMS
#
# Code references:
# - sph_ird_wave_calib_run.c
#
Parameter Name:    ESO QC WAVECAL C1 RMS
Class:             header|qc-log
Context:           process
Type:              double
Value Format:       %.2f
Unit:              micron/pix
Comment Field:     RMS of mean slope of wavelength solution [micron/pix]
Description:
#
# Code define: SPH_IRD_KEYWORD_WAVECALIB_YO
#
# Code references:
# - sph_ird_wave_calib_run.c
#
Parameter Name:    ESO QC WAVECAL YO COL
Class:             header|qc-log
Context:           process
Type:              double
Value Format:       %.2f
Unit:              micron
Comment Field:     Minimum wavelength for spectral region/column [micron]
Description:
#
# Code define: SPH_IRD_KEYWORD_WAVECALIB_C1
```



```
#
#   Code references:
#   - sph_ird_wave_calib_run.c
#
Parameter Name:   ESO QC WAVECAL C1 COL
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:            micron/pix
Comment Field:    Slope of wavelength solution for spectral region/column [micron/pix]
Description:
#
# Code define: SPH_IRD_KEYWORD_WAVECALIB_CHI
#
#   Code references:
#   - sph_ird_wave_calib_run.c
#
Parameter Name:   ESO QC WAVECAL CHI2 COL
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:            micron2
Comment Field:    CHI2 of wavelength solution for spectral region/column [micron2]
Description:
#
# Code define: SPH_IRD_KEYWORD_WAVECALIB_QC_LAM
#
#   Code references:
#   - sph_ird_wave_calib_run.c
#
Parameter Name:   ESO QC WAVECAL LAM LINE
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:            micron
Comment Field:    Wavelength of line [micron]
Description:
#
# Code define: SPH_IRD_KEYWORD_WAVECALIB_QC_LAMRMS
#
#   Code references:
#   - sph_ird_wave_calib_run.c
#
Parameter Name:   ESO QC WAVECAL LAM RMS LINE
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:            micron
Comment Field:    RMS of line wavelength [micron]
Description:
```



```
#
# Code define: SPH_IRD_KEYWORD_FLUX_LEFT_CORO
#
#   Code references:
#     - sph_ird_flux_calib_run.c
#
Parameter Name:   ESO QC IRD COUNT LEFT CORO ON
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:            ADU
Comment Field:    Total star flux in left coro image [ADU]
Description:
#
# Code define: SPH_IRD_KEYWORD_FLUX_RIGHT_CORO
#
#   Code references:
#     - sph_ird_flux_calib_run.c
#
Parameter Name:   ESO QC IRD COUNT RIGHT CORO ON
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:            ADU
Comment Field:    Total star flux in right coro image [ADU]
Description:
#
# Code define: SPH_IRD_KEYWORD_FLUX_LEFT_NO_CORO
#
#   Code references:
#     - sph_ird_flux_calib_run.c
#
Parameter Name:   ESO QC IRD COUNT LEFT CORO OFF
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:            ADU
Comment Field:    Total star flux in left non-coro image [ADU]
Description:
#
# Code define: SPH_IRD_KEYWORD_FLUX_RIGHT_NO_CORO
#
#   Code references:
#     - sph_ird_flux_calib_run.c
#
Parameter Name:   ESO QC IRD COUNT RIGHT CORO OFF
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:            ADU
```



Comment Field: Total star flux in right non-coro image [ADU]

Description:

#

# Code define: SPH\_IRD\_KEYWORD\_DISTMAP\_NPOINTS\_OBS

#

# Code references:

# - sph\_ird\_distortion\_map\_run.c

#

Parameter Name: ESO QC DISTMAP NPOINTS OBS

Class: header|qc-log

Context: process

Type: int

Value Format: %d

Unit: 1

Comment Field: Number of points found in observed pattern [1]

Description:

#

# Code define: SPH\_IRD\_KEYWORD\_DISTMAP\_NPOINTS\_IN

#

# Code references:

# - sph\_ird\_distortion\_map\_run.c

#

Parameter Name: ESO QC DISTMAP NPOINTS IN

Class: header|qc-log

Context: process

Type: int

Value Format: %d

Unit: 1

Comment Field: Number of points expected in input pattern [1]

Description:

#

# Code define: SPH\_IRD\_KEYWORD\_DISTMAP\_OPTICAL\_AXIS\_X

#

# Code references:

# - sph\_ird\_distortion\_map\_run.c

#

Parameter Name: ESO QC DISTMAP OPT AXIS X

Class: header|qc-log

Context: process

Type: double

Value Format: %.2f

Unit: px

Comment Field: X position of optical axis [px]

Description:

#

# Code define: SPH\_IRD\_KEYWORD\_DISTMAP\_OPTICAL\_AXIS\_Y

#

# Code references:

# - sph\_ird\_distortion\_map\_run.c

#

Parameter Name: ESO QC DISTMAP OPT AXIS Y

Class: header|qc-log

Context: process

Type: double

```

Value Format:      %.2f
Unit:             px
Comment Field:    Y position of optical axis [px]
Description:
#
# Code define: SPH_IRD_KEYWORD_FLAT_FPN_LEFT
#
#   Code references:
#     - sph_ird_instrument_flat_run.c
#
Parameter Name:   ESO QC FPN LEFT
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             perc. of mean
Comment Field:    FPN of left frame [perc. of mean]
Description:
#
# Code define: SPH_IRD_KEYWORD_FLAT_RMS_LEFT
#
#   Code references:
#     - sph_ird_instrument_flat_run.c
#
Parameter Name:   ESO QC RMS LEFT
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             1
Comment Field:    RMS of left frame [1]
Description:
#
# Code define: SPH_IRD_KEYWORD_FLAT_NONLIN_FACTOR_LEFT
#
#   Code references:
#     - sph_ird_instrument_flat_run.c
#
Parameter Name:   ESO QC FLAT NONLINEARITY L
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             1
Comment Field:    Non-linearity factor of left frame [1]
Description:
#
# Code define: SPH_IRD_KEYWORD_FLAT_MEAN_COUNT_LEFT
#
#   Code references:
#     - sph_ird_instrument_flat_run.c
#
Parameter Name:   ESO QC FLAT MEAN LEFT
Class:            header|qc-log

```



```
Context:      process
Type:         double
Value Format:  %.2f
Unit:         ADU
Comment Field: Mean value of left frame [ADU]
Description:
#
# Code define: SPH_IRD_KEYWORD_FLAT_FPN_RIGHT
#
#   Code references:
#   - sph_ird_instrument_flat_run.c
#
Parameter Name:  ESO QC FPN RIGHT
Class:          header|qc-log
Context:        process
Type:          double
Value Format:    %.2f
Unit:          perc. of mean
Comment Field:  FPN of right frame [perc. of mean]
Description:
#
# Code define: SPH_IRD_KEYWORD_FLAT_RMS_RIGHT
#
#   Code references:
#   - sph_ird_instrument_flat_run.c
#
Parameter Name:  ESO QC RMS RIGHT
Class:          header|qc-log
Context:        process
Type:          double
Value Format:    %.2f
Unit:          1
Comment Field:  RMS of right frame [1]
Description:
#
# Code define: SPH_IRD_KEYWORD_FLAT_NONLIN_FACTOR_RIGHT
#
#   Code references:
#   - sph_ird_instrument_flat_run.c
#
Parameter Name:  ESO QC FLAT NONLINEARITY R
Class:          header|qc-log
Context:        process
Type:          double
Value Format:    %.2f
Unit:          1
Comment Field:  Non-linearity factor of right frame [1]
Description:
#
# Code define: SPH_IRD_KEYWORD_FLAT_MEAN_COUNT_RIGHT
#
#   Code references:
#   - sph_ird_instrument_flat_run.c
#
```



Parameter Name: ESO QC FLAT MEAN RIGHT  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: Mean value of right frame [ADU]  
Description:  
#  
# Code define: SPH\_IRD\_KEYWORD\_FLAT\_LAMP\_FLUX\_LEFT  
#  
# Code references:  
# - sph\_ird\_instrument\_flat\_run.c  
#  
Parameter Name: ESO QC LAMP FLUX AVG LEFT  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU/s  
Comment Field: Average lamp flux in left frame [ADU/s]  
Description:  
#  
# Code define: SPH\_IRD\_KEYWORD\_FLAT\_LAMP\_FLUX\_RIGHT  
#  
# Code references:  
# - sph\_ird\_instrument\_flat\_run.c  
#  
Parameter Name: ESO QC LAMP FLUX AVG RIGHT  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU/s  
Comment Field: Average lamp flux in right frame [ADU/s]  
Description:  
#  
# Code define: SPH\_IRD\_KEYWORD\_FLAT\_LAMP\_COUNTS\_LEFT  
#  
# Code references:  
# - sph\_ird\_instrument\_flat\_run.c  
#  
Parameter Name: ESO QC LAMP ADU AVG LEFT  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU/s  
Comment Field: Average lamp flux in right frame [ADU/s]  
Description:  
#  
# Code define: SPH\_IRD\_KEYWORD\_FLAT\_LAMP\_COUNTS\_RIGHT  
#  
# Code references:



```
# - sph_ird_instrument_flat_run.c
#
Parameter Name:   ESO QC LAMP ADU AVG RIGHT
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU
Comment Field:    Average total lamp counts in right frame [ADU]
Description:
#
# Code define: SPH_IRD_KEYWORD_FLAT_LAMP_FLUX_STDEV_LEFT
#
# Code references:
# - sph_ird_instrument_flat_run.c
#
Parameter Name:   ESO QC LAMP FLUX STDEV LEFT
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU/s
Comment Field:    SDEV of avg. lamp flux in left frame [ADU/s]
Description:
#
# Code define: SPH_IRD_KEYWORD_FLAT_LAMP_FLUX_STDEV_RIGHT
#
# Code references:
# - sph_ird_instrument_flat_run.c
#
Parameter Name:   ESO QC LAMP FLUX STDEV RIGHT
Class:            header|qc-log
Context:          process
Type:             double
Value Format:      %.2f
Unit:             ADU/s
Comment Field:    SDEV of avg. lamp flux in right frame [ADU/s]
Description:
```

## A.3 IFS

```
#
# Code define: SPH_IFS_KEYWORD_SPECPOS_QC_NREGS
#
# Code references:
# - sph_ifs_spectra_positions_run.c
#
Parameter Name:   ESO QC NUMBER SPECTRA
Class:            header|qc-log
Context:          process
Type:             int
Value Format:      %d
```



Unit: 1  
Comment Field: Number of spectra found [1]  
Description: Number of spectra found

#  
# Code define: SPH\_IFS\_KEYWORD\_SPECPOS\_QC\_THRESHOLD  
#  
# Code references:  
# - sph\_ifs\_spectra\_positions\_run.c  
#

Parameter Name: ESO QC THRESHOLD USED  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: Threshold used for spectra detection [ADU]  
Description: Threshold used for spectra detection

#  
# Code define: SPH\_IFS\_KEYWORD\_SPECPOS\_QC\_SCALE  
#  
# Code references:  
# - sph\_ifs\_spectra\_positions\_run.c  
#

Parameter Name: ESO QC SCALE MEASURED  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: 1  
Comment Field: Scale of specpos model as measured [1]  
Description: Scale of specpos model as measured

#  
# Code define: SPH\_IFS\_KEYWORD\_CAL\_BG\_QC\_MEAN  
#  
# Code references:  
# - sph\_ifs\_cal\_background\_run.c  
#

Parameter Name: ESO QC BACKGROUND MEAN  
Class: header|qc-log  
Context: process  
Type: double  
Value Format: %.2f  
Unit: ADU  
Comment Field: background mean value [ADU]  
Description: Background mean value

#  
# Code define: SPH\_IFS\_KEYWORD\_CAL\_BG\_QC\_RMS  
#  
# Code references:  
# - sph\_ifs\_cal\_background\_run.c



```
#
Parameter Name:    ESO QC BACKGROUND RMS
Class:             header|qc-log
Context:           process
Type:              double
Value Format:       %.2f
Unit:              ADU
Comment Field:     Background RMS [ADU]
Description:       Bckground RMS

#
# Code define: SPH_IFS_KEYWORD_CAL_BG_QC_MEDIAN
#
#   Code references:
#   - sph_ifs_cal_background_run.c
#
Parameter Name:    ESO QC BACKGROUND MEDIAN
Class:             header|qc-log
Context:           process
Type:              double
Value Format:       %.2f
Unit:              ADU
Comment Field:     Background median value [ADU]
Description:       Background median value

#
# Code define: SPH_IFS_KEYWORD_PREAMPCORR_MEAN
#
#
Parameter Name:    ESO QC PREAMP CORR MEAN
Class:             header|qc-log
Context:           process
Type:              string
Value Format:       %30s
Unit:              1
Comment Field:     Mean value of preamp correlation [1]
Description:       Mean value of preamp correlation

#
# Code define: SPH_IFS_KEYWORD_PREAMPCORR_MEDIAN
#
#
Parameter Name:    ESO QC PREAMP CORR MEDIAN
Class:             header|qc-log
Context:           process
Type:              string
Value Format:       %30s
Unit:              1
Comment Field:     Median value of preamp correlation [1]
Description:       Median value of preamp correlation

#
# Code define: SPH_IFS_KEYWORD_PREAMPCORR_RMS
#
```



```
#
Parameter Name:    ESO QC PREAMP CORR RMS
Class:             header|qc-log
Context:           process
Type:              string
Value Format:       %30s
Unit:              1
Comment Field:     RMS of preamp correlation [1]
Description:       RMS of preamp correlation

#
# Code define: SPH_IFS_KEYWORD_DISTMAP_NPOINTS_OBS
#
#   Code references:
#   - sph_ifs_distortion_map_run.c
#
Parameter Name:    ESO QC DISTMAP NPOINTS OBS
Class:             header|qc-log
Context:           process
Type:              int
Value Format:       %d
Unit:              1
Comment Field:     Number of points observed for distortion map [1]
Description:       Number of points observed for distortion map

#
# Code define: SPH_IFS_KEYWORD_DISTMAP_POLFIT_CHIX
#
#   Code references:
#   - sph_ifs_spectra_positions_run.c
#
Parameter Name:    ESO QC DISTMAP POLFIT CHIX
Class:             header|qc-log
Context:           process
Type:              double
Value Format:       %.2f
Unit:              1
Comment Field:     Chi squared of the polynomial distortion fit [1]
Description:       Red. chi squared of the polynomial distortion fit

#
# Code define: SPH_IFS_KEYWORD_DISTMAP_POLFIT_CHIY
#
#   Code references:
#   - sph_ifs_spectra_positions_run.c
#
Parameter Name:    ESO QC DISTMAP POLFIT CHIY
Class:             header|qc-log
Context:           process
Type:              double
Value Format:       %.2f
Unit:              1
Comment Field:     Chi squared of the polynomial distortion fit [1]
Description:       Red. chi squared of the polynomial distortion fit
```

## A.4 ZIMPOL

There are currently no specific ZIMPOL QC keywords. See common.