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### Change record

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2.0	29/06/2006	sec 6,10	Update, added information on table products content
3.0	17/01/2007	all	Update, match new release, more figures to clarify algorithm and recipe description
4.0	15/05/2007	sec 3,11	Update, more accurate sky subtraction, WCS, fixed some bugs on Strehl computation
5.0	19/10/2007	sec 3	Update
6.0	02/04/2008	sec 3,5,10,11	Update
7.0	15/07/2008		Update
8.0	20/10/2008		Update
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# 1 Introduction

## 1.1 Purpose

The SINFONI pipeline is a subsystem of the *VLT Data Flow System* (DFS). Its target user is ESO *Data Products Department* (DPD) in the generation of master calibration data, in the reduction of scientific exposures, and in the data quality control. It should also serve as a quick look tool for *Paranal Science Operations* (PSO). Additionally, the SINFONI 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 SINFONI data reduction sequence with the SINFONI pipeline.

This manual is a complete description of the data reduction recipes implemented by the the SINFONI pipeline, reflecting the status of the SINFONI pipeline as of April 07, 2011 (version 2.2.5).

## 1.2 Acknowledgements

The SINFONI pipeline is based on the SPIFFI Data Reduction Software developed by the Max-Planck-Institut für extraterrestrische Physik (MPE). We would like to thank the SPIFFI team for providing ESO with a complete and efficient data reduction software and for their help in documenting, testing, debugging the recipes and the pipeline during several commissioning and science verifications phases. We are particularly grateful to the MPE responsables for the data reduction: Jurgen Schreiber, Matthew Horrobin and Roberto Abuter for their contributions and support.

Release 1.2.0 benefited from the feedback provided by the SINFONI SV team and SINFONI instrument operations team. In particular we would like to thank Wolfgang Hummel and Juha Runanen for extensively testing and improving the pipeline and documentation, as well as Jochen Liske for proof reading the manual.

Very useful was the collaboration with Richard Davies from MPE which lead to an improvement of the sky subtraction quality since release 1.6.0.

From May 2009 till end of March 2009 Andrea Modigliani passed the responsibility for this project to Konstantin Mirny. Then Andrea continued to be responsible of this project.

## 1.3 Scope

This document describes the SINFONI pipeline used at ESO-Garching and ESO-Paranal for the purpose of data assessment and data quality control.

Updated versions of the present document may be found on [1]. For general information about the current instrument pipelines status we remind the user of [2]. Quality control information are at [3].

Additional information on the Common Pipeline Library (CPL) and ESOREX can be found respectively at [4], [5]. The Gasgano front end is described in [6]. A description of the instrument is in [7]. The SINFONI instrument user manual is in [8] while results of Science Verifications (SV) are at [9]. A clear and compact description of the SINFONI pipeline is in [15].

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## 1.4 Reference documents

- [1] SINFONI Pipeline Users' Manual VLT-MAN-ESO-19500-3600  
[www.eso.org/pipelines](http://www.eso.org/pipelines)
- [2] Current pipeline status  
[www.eso.org/observing/dfo/quality/pipeline-status.html](http://www.eso.org/observing/dfo/quality/pipeline-status.html)
- [3] ESO-Data Flow Operation home page <http://www.eso.org/observing/dfo/quality/>
- [4] CPL home page [www.eso.org/cpl](http://www.eso.org/cpl)
- [5] ESOREX home page [www.eso.org/cpl/esorex.html](http://www.eso.org/cpl/esorex.html)
- [6] Gasgano User's Manual VLT-PRO-ESO-19000-1932
- [7] SINFONI home page  
[www.eso.org/sci/facilities/paranal/instruments/sinfoni](http://www.eso.org/sci/facilities/paranal/instruments/sinfoni)
- [8] VLT SINFONI User Manual VLT-MAN-ESO-14700-3517  
[www.eso.org/instruments/sinfoni/doc](http://www.eso.org/instruments/sinfoni/doc)
- [9] SINFONI SV home page [www.eso.org/science/vltsv/sinfonisv](http://www.eso.org/science/vltsv/sinfonisv)
- [10] VLT Data Flow System Specifications for Pipeline and Quality Control  
VLT-SPE-ESO-19600-1233
- [11] DFS Pipeline & Quality Control – User Manual VLT-MAN-ESO-19500-1619
- [12] ESO DICB – Data Interface Control Document GEN-SPE-ESO-00000-0794
- [13] Common Pipeline Library User Manual VLT-MAN-ESO-19500-2720
- [14] SINFONI Calibration Plan VLT-PLA-ESO-14700-2617
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- [18] *A method to remove residual OH emission from near infrared spectra* MNRAS, **375**, 1099 (2007).
- [19] *SINFONI data reduction cookbook* [VLT-MAN-ESO-14700-4037.pdf](http://www.eso.org/instruments/sinfoni/doc/VLT-MAN-ESO-14700-4037.pdf)

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## 2 Overview

In collaboration with instrument consortia, the Pipeline Systems Department (PSD) of the Software Development 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 bias frames, super-flats, wavelength dispersion solutions).

**Science product creation:** using pipeline-generated master calibration products, science products are produced for the supported instrument modes (*e.g.*, combined ISAAC jitter stacks; bias-corrected, flat-fielded FORS images, wavelength-calibrated UVES spectra). 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* [6] and *EsoRex* [5], both included in the pipeline distribution (see Appendix A, page 122). These applications can also be downloaded separately from [www.eso.org/gasgano](http://www.eso.org/gasgano) and [www.eso.org/cpl/esorex.html](http://www.eso.org/cpl/esorex.html). An illustrated introduction to Gasgano is provided in the "Quick Start" section of this manual (see page 19).

The SINFONI instrument and the different types of SINFONI raw frames and auxiliary data are described in Sections 4, 7, and 8.

A brief introduction to the usage of the available reduction recipes using Gasgano or EsoRex is presented in Section 5. In section 6 we advise the user about known data reduction problems providing also possible solutions.

An overview of the data reduction, what are the input data, and the recipes involved in the calibration cascade is provided in section 9.

More details on what are inputs, products, quality control measured quantities, and controlling parameters of each recipe is given in section 10.

More detailed descriptions of the data reduction algorithms used by the individual pipeline recipes can be found in Section 11.

In Appendix A the installation of the SINFONI pipeline recipes is described and in Appendix B a list of used abbreviations and acronyms is given.

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### 3 Recent improvements

As we made two releases close one the other each with relevant changes we indicate here all the most recent changes.

#### 3.1 What's new on release 2.2.5

The following major improvements has been realised on the SINFONI pipeline:

- Updated CPL and Esorex release.
- Corrected WCS CUNIT2/3 and CRPIX to be compliant to FITS standard.



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## 4 SINFONI Instrument Description

SINFONI has been developed by ESO and the Max-Planck-Institut für extraterrestrische Physik (MPE) in Garching in collaboration with NOVA. The instrument has been made available to the community and started operations in Paranal on April 1<sup>st</sup>, 2005.

In this chapter a brief description of the SINFONI instrument is given. A more complete documentation can be found in the SINFONI User Manual, downloadable from

[www.eso.org/sci/facilities/paranal/instruments/sinfoni](http://www.eso.org/sci/facilities/paranal/instruments/sinfoni).

### 4.1 Instrument overview

SINFONI is composed of two subsystems: the Multi-Application Curvature Adaptive Optics unit (MACAO, developed by ESO), which allows diffraction and seeing limited observations; and the SPectrograph for Integral Faint Field Imaging, a near-infrared (1.05 - 2.45  $\mu\text{m}$ ) integral field spectrograph, (SPIFFI, developed by MPE). It is described with more details in [10], [17] and [18].

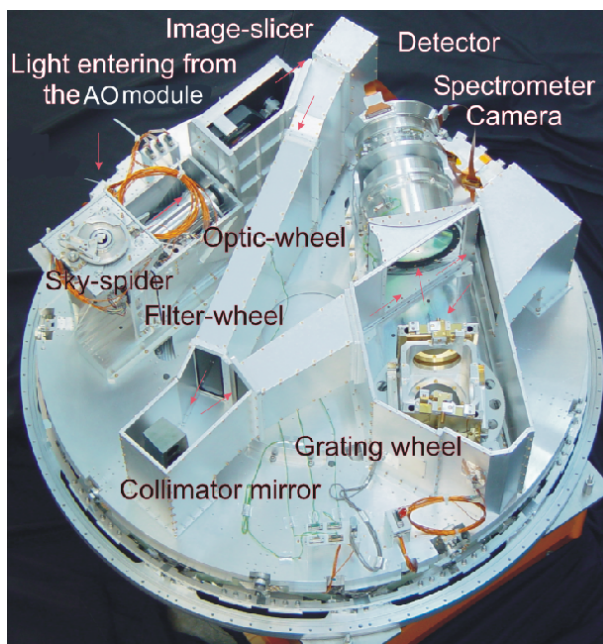


Figure 4.1.1: An inside view of SPIFFI: The cryostat cover and the reinforcing structure have been removed to provide a free view on the opto-mechanical components of SPIFFI. The light enters from the top, and passes the sky-spider. The pre-optics with a filter-wheel and interchangeable lenses provides three different image scales. The image slicer re-arranges the two-dimensional field into a pseudo-long slit, which is perpendicular to the base plate. Three diamond turned mirrors collimate the light onto the gratings. In total, four gratings are implemented on the grating drive. A multiple-lens system then focuses the spectra on a Rockwell HAWAII array. The diameter of the instrument is 1.3m.

The spectrograph operates with 4 gratings (J, H, K, H+K) providing a spectral resolution around 2000, 3000,

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4000 in J, H, K, respectively, and 1500 in H+K - each wavelength band fitting fully on the 2048 pixels of the Hawaii 2RG (2kx2k) detector in the dispersion direction. The SINFONI field of view on the sky is sliced into 32 slices. Pre-optics allow to chose the width of the slices. The choices are 250, 10 and 25 mas/pixel, leading to field of views on the sky of 8"x8", 3"x3", or 0.8"x0.8" respectively. On raw frames each pixel images a rectangular region on the sky (125x250, 50x100, or 12.5x25 mas). Each SINFONI FOV image slice corresponds to a so called detector slitlet. Each one of the 32 slitlets is imaged onto 64 pixels of the detector. Thus one obtains 32x64 spectra of the imaged region on the sky.

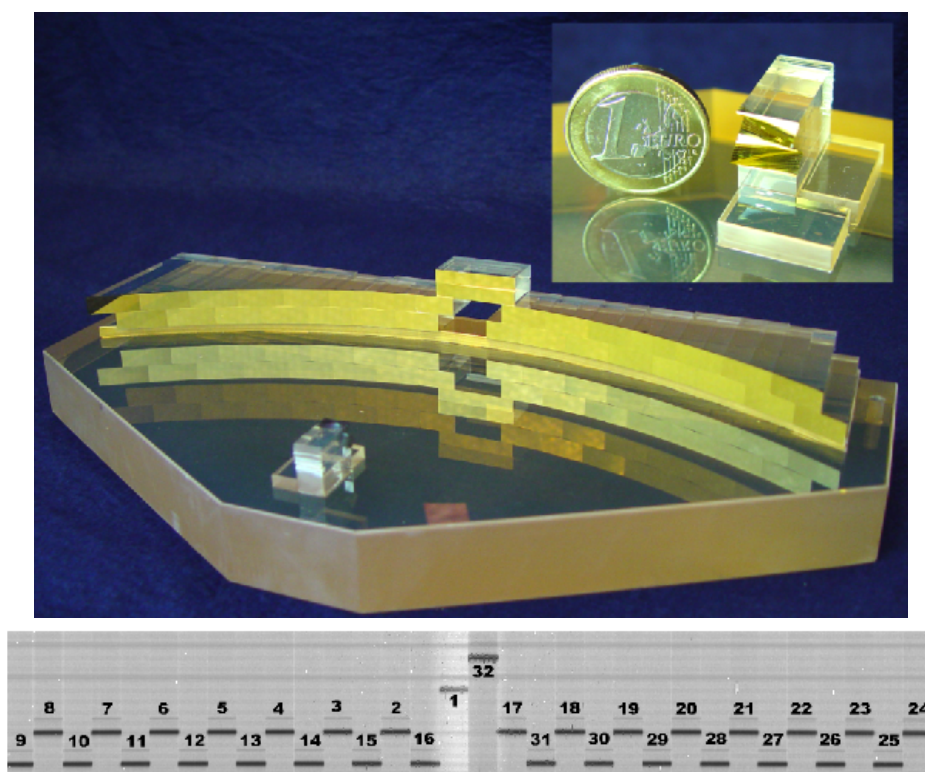


Figure 4.1.2: SPIFFI image slicer (top): The light enters through the hole in the big slicer. A stack of 32 small mirrors, the small slicer (also shown in the sub-panel), slices the image and redirects the light towards the 32 mirrors of the big slicer, which re-arranges the slitlets into a 31 cm long pseudo-slit (bottom). The layout of the slitlets on a raw SPIFFI frame.

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## 5 Quick start

This section describes the most immediate usage of the SINFONI pipeline recipes.

### 5.1 SINFONI pipeline recipes

The current SINFONI pipeline is based on a set of 6 stand-alone recipes involved in the data reduction cascade:

**sinfo\_rec\_detlin** to evaluate the detector linearity and generate a corresponding non linear pixel map.

**sinfo\_rec\_mdark** to create a master dark and a hot-pixel map.

**sinfo\_rec\_mflat** to create a master flat and a map of pixels which have intensities greater than a given threshold.

**sinfo\_rec\_distortion** to compute the optical distortions and slitlets distances.

**sinfo\_rec\_wavecal** for wavelength calibration.

**sinfo\_rec\_jitter** for PSF, telluric standard and other science data reduction.

Other 3 stand-alone recipes are also provided, used for quality control:

**sinfo\_rec\_pupil** for PUPIL data reduction (for Paranal operations, to monitor telescope pupil centering on the SINFONI FOV)

**sinfo\_rec\_lingain** for detector characterization: it computes detector's linearity and gain and generates a corresponding non linear pixel map, sharing implementation across pipelines.

**sinfo\_rec\_dark\_detmon** Master dark and detector signal non uniformity map generation (recipe used for quality control)

Additional 13 stand-alone recipes are also provided, that perform useful tasks:

**sinfo\_utl\_bp\_mask\_add** to coadd bad pixel maps.

**sinfo\_utl\_cube2ima** to collapse a cube to an image over a given wavelength range.

**sinfo\_utl\_cube2spectrum** to extract a spectrum from a cube.

**sinfo\_utl\_cube\_arith** to perform cube arithmetics.

**sinfo\_utl\_cube\_combine** to combine and coadd cubes or mosaics.

**sinfo\_utl\_cube\_create** to create a cube out of any input raw on/off frame pair.

**sinfo\_utl\_eff** to compute efficiency.

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**sinfo\_utl\_ima\_arith** to do image arithmetics.

**sinfo\_utl\_ima\_line\_corr** to correct detector bad rows generated by the data processing hardcoded at the detector level.

**sinfo\_utl\_skycor** to correct object spectra from sky residuals.

**sinfo\_utl\_skymap** to flag sky lines as bad pixels in a “sky map” (for Paranal operations, to prepare input data of the SINFONI Real Time Display).

**sinfo\_utl\_spectrum\_divide\_by\_blackbody** to divide a spectrum by a black body spectrum.

**sinfo\_utl\_spectrum\_wavelength\_shift** to shift in wavelength a spectrum.

## 5.2 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.*, BIAS, "to which group do I belong?", *e.g.*, to a particular Observation Block 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.

An instrument pipeline consists of a set of data processing modules that can be called from different host applications, either from the command line 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.

### 5.2.1 Using Gasgano

To get familiar with the SINFONI pipeline recipes and their usage, it is advisable to begin with *Gasgano*, because it provides a complete graphic interface for data browsing, classification and association, and offers several other utilities such as easy access to recipes documentation and preferred data display tools.

*Gasgano* can be started from the system prompt in the following way:

```
gasgano &
```

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The *Gasgano* main window will appear. On Figure 5.2.1 (next page), a view on a set of SINFONI IFU data is shown as an example. *Gasgano* can be pointed to the directories where the data to be handled are located using the navigation panels accessible via the *Add/Remove Files* entry of the *File* menu (shown on the upper left of the figure).

The data are hierarchically organised as preferred by the user. After each file name are shown the classification, the instrument setup id (which indicates the band), the instrument pre-optic (which indicates the camera setting), the template exposure number and the number of exposures in the template, and the value of the DPR.TYPE.

More information about a single frame can be obtained by clicking on its name: the corresponding FITS file header will be displayed on the bottom panel, where specific keywords can be opportunely filtered and searched. Images and tables may be easily displayed using the viewers specified in the appropriate *Preferences* fields.

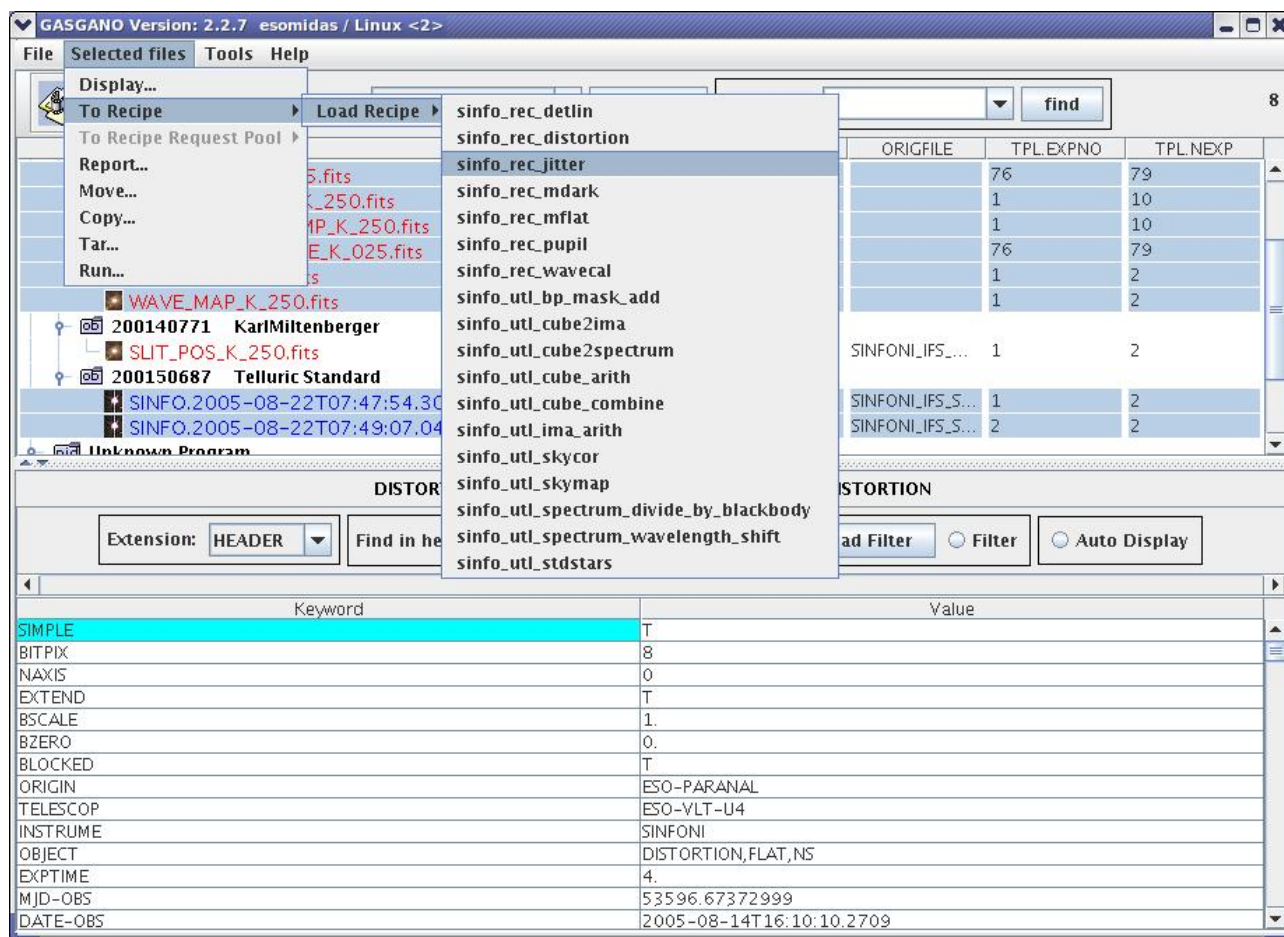


Figure 5.2.1: The *Gasgano* main window.

Frames can be selected from the main window for being processed by the appropriate recipe: on Figure 5.2.2, the standard star frame and a sky frame, already produced master bad pixel map and master flat field frames, together with distortion and slitlet distance tables, and the necessary static calibration tables, are all selected and sent to the *sinfo\_rec\_stdstar* recipe. This will open a *Gasgano* recipe execution window (see Figure 5.2.3),



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having all the specified files listed in its *Input Frames* panel.

Help about the recipe may be obtained from the *Help* menu. Before launching the recipe, its configuration may be opportunely modified on the *Parameters* panel (on top). The window contents might be saved for later use by selecting the *Save Current 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* panel at bottom, and in case of successful completion the products will be listed on the *Output Frames* panel, where they can be easily viewed and located back on the Gasgano main window.

Please refer to the *Gasgano User's Manual* [6] for a more complete description of the *Gasgano* interface.

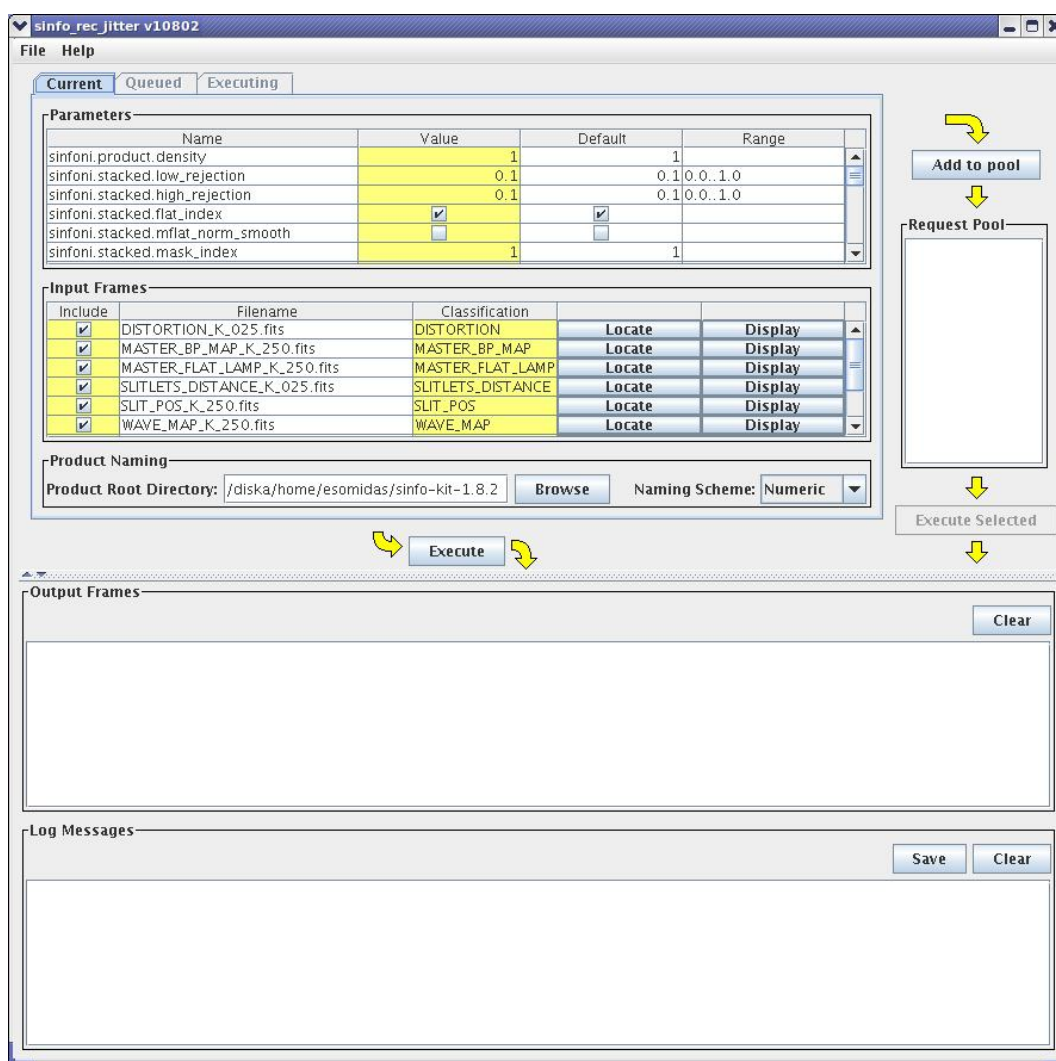


Figure 5.2.2: Selecting files to be processed by a SINFONI pipeline recipe.

Please refer to the *Gasgano User's Manual* [7] for a more complete description of the *Gasgano* interface.

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**sinfo\_rec Jitter v10802**

File Help

Current Queued Executing

**Parameters**

Name	Value	Default	Range
sinfo.product.density	1	1	
sinfo.stacked.low_rejection	0.1	0.1	0.0..1.0
sinfo.stacked.high_rejection	0.1	0.1	0.0..1.0
sinfo.stacked.flat_index	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
sinfo.stacked.mflat_norm_smooth	<input type="checkbox"/>	<input type="checkbox"/>	
sinfo.stacked.mask_index	1	1	

**Input Frames**

Include	Filename	Classification	Locate	Display
<input checked="" type="checkbox"/>	DISTORTION_K_025.fits	DISTORTION	Locate	Display
<input checked="" type="checkbox"/>	MASTER_BP_MAP_K_250.fits	MASTER_BP_MAP	Locate	Display
<input checked="" type="checkbox"/>	MASTER_FLAT_LAMP_K_250.fits	MASTER_FLAT_LAMP	Locate	Display
<input checked="" type="checkbox"/>	SLITLETS_DISTANCE_K_025.fits	SLITLETS_DISTANCE	Locate	Display
<input checked="" type="checkbox"/>	SLIT_POS_K_250.fits	SLIT_POS	Locate	Display
<input checked="" type="checkbox"/>	WAVE_MAP_K_250.fits	WAVE_MAP	Locate	Display

**Product Naming**

Product Root Directory: /diska/home/esomidas/sinfo-kit-1.8.2  Naming Scheme: Numeric

**Request Pool**

**Output Frames**

Filename	Classification	Locate	Display
out_sky00_0002.fits	SKY_STACKED_DUMMY	Locate	Display
out_sky_stack_dist0_0002.fits	SKY_STACKED_DIST	Locate	Display
out_stack_mflat_dist_0003.fits	MFLAT_STACKED_DIST	Locate	Display
out_stack0_0002.fits	STD_NODDING_STACKED	Locate	Display
out_resampled_obj0_0002.fits	RESAMPLED_OBJ	Locate	Display
out_resampled_sky0_0002.fits	RESAMPLED_SKY	Locate	Display
out_resampled_flat0_0002.fits	RESAMPLED_FLAT_LAMP	Locate	Display
out_sky_cube00_0002.fits	OBJ_SKY	Locate	Display

**Log Messages**

/diska/home/esomidas/sinfo-kit-1.8.2/out\_objnod\_bpmap\_0002.fits  
/diska/home/esomidas/sinfo-kit-1.8.2/out\_ao\_performance\_0002.fits  
/diska/home/esomidas/sinfo-kit-1.8.2/out\_encircled\_energy\_0002.fits  
/diska/home/esomidas/sinfo-kit-1.8.2/out\_psf\_0002.fits  
/diska/home/esomidas/sinfo-kit-1.8.2/out\_std\_star\_spectrum\_0002.fits  
/diska/home/esomidas/sinfo-kit-1.8.2/out\_starspectrum\_0001.fits  
Completion status: SUCCESS

Figure 5.2.3: The Gasgano recipe execution window.

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### 5.2.2 Using EsoRex

*EsoRex* is a command line utility for running pipeline recipes. It may be embedded by users into data reduction scripts for the automation of processing tasks. On the other side, *EsoRex* doesn't offer all the facilities available with *Gasgano*, and the user must classify and associate the data using the information contained in the FITS header keywords (see Section 7.2, page 39). The user should also take care of defining the input set-of-frames and the 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 filenames must be listed together with their DO category <sup>1</sup> in an ASCII file, the *set-of-frames* (SOF), that is required when launching a recipe. <sup>2</sup>

Here is an example of SOF, valid for the *sinfo\_rec\_wavecald* recipe <sup>3</sup>:

```

/file_path/SINFO.2004-08-14T10:20:56.497.fits    WAVE_LAMP
/file_path/SINFO.2004-08-14T10:22:44.285.fits    WAVE_LAMP
/file_path/xenon.fits                            REF_LINE_ARC
/file_path/MASTER_BP_MAP_H_250.fits             MASTER_BP_MAP
/file_path/MASTER_LAMP_FLAT_H_250.fits          MASTER_FLAT_LAMP
/file_path/DISTORTION_H.fits                     DISTORTION
/file_path/drs_setup_wave.fits                   DRS_SETUP_WAVE
/file_path/SLIT_POS_H_250.fits                   SLIT_POS

```

It contains for each input frame the full path file name and its DO category. The pipeline recipe will access the listed files when required by the reduction algorithm.

Note that the SINFONI pipeline recipes do not verify in any way the correctness of the classification tags specified by the user in the SOF. In the above example, the recipe *sinfo\_rec\_wavecald* will treat the frame `/file_path/SINFO.2004-08-14T10:20:56.497.fits` as a `WAVE_LAMP`, the frame `/file_path/MASTER_BP_MAP_H_250.fits` as a `MASTER_BP_MAP`, etc., even when they do not contain this type of data. The recipe will also assume that all frames are associated correctly, *i.e.*, that they all come from the same band and pre-optic, and that the appropriate calibration files have been specified.

The reason of this lack of control is that the SINFONI recipes are just the DRS component of the complete pipeline running on Paranal, where the task of data classification and association is carried out by separate applications. Moreover, using *Gasgano* as an interface to the pipeline recipes will always ensure a correct classification of all the data frames, assigning the appropriate DO category to each one of them (see Section 5.2.1, page 20).

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.

<sup>1</sup>The indicated *DO category* is a label assigned to any data type after it has been classified, which is then used to identify the frames listed in the *set-of-frames*

<sup>2</sup>The set-of-frames corresponds to the *Input Frames* panel of the *Gasgano* recipe execution window (see Figure 5.2.3, page 23).

<sup>3</sup>We list the file `SLIT_POS_H_250.fits` as an input file, as, for robustness, we suggest the user to set the parameter `slit-pos_bootstrap_switch` to `FALSE`. A different setting would allow to reduce the data without including the `SLIT_POS` table



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**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 [5]) 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**

**Recipe configuration:** Each pipeline recipe may be assigned an *EsoRex* configuration file, containing the default values of the parameters related to that recipe.<sup>4</sup> 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 filename extension `.rc`. For instance, the recipe `sinfo_rec_wavecal` has its *EsoRex* generated configuration file named `sinfo_rec_wavecal.rc`, and is generated with the command:

**esorex - -create-config sinfo\_rec\_wavecal**

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

```
# --stack-warpfix_kernel
# Warpfix kernel: (tanh | sinc | sinc2 | lanczos | hamming | hann)
sinfoni.stacked.warpfix_kernel=tanh
```

In this example, the parameter `sinfoni.stacked.warpfix_kernel` is set to the value `tanh`. 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 SINFONI pipeline are designed to implement a cascade of macro 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**<sup>5</sup>.

<sup>4</sup>The *EsoRex* recipe configuration file corresponds to the *Parameters* panel of the *Gasgano* recipe execution window (see Figure 5.2.3, page 23).

<sup>5</sup>If a number of recipe parameters are specified on the command line, the given values will be used in the created configuration file.

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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 10 and their role is described in Section 11.

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.

**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 *sinfo\_rec\_wavecal* for processing the files specified in the set-of-frames *sinfo\_rec\_wavecal.sof*:

**esorex sinfo\_rec\_wavecal sinfo\_rec\_wavecal.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 *sinfo\_rec\_wavecal* recipe *wcal-pixel\_tol* parameter to 3.0, the following should be typed:

**esorex sinfo\_rec\_wavecal - -wcal-pixel\_tol=3.0 sinfo\_rec\_wavecal.sof**

For more information on *EsoRex*, see [www.eso.org/cpl/esorex.html](http://www.eso.org/cpl/esorex.html).

### 5.3 Example of data reduction using EsoRex

A simple, typical data reduction procedure is described here.<sup>6</sup>

We suggest the user to organize his data per type, observed band and camera setting. Dark frames may be grouped per detector DIT, frames to compute distortion and frames to compute detector non linearities may be organized per observed band. The detector DIT is given by the value of the FITS keyword DET DIT<sup>7</sup>. The observed band is indicated by the value of the FITS keyword INS SETUP ID. The camera setting is indicated by the value of INS OPTI1 NAME. In the examples below we suppose the user has data acquired in band K and with the 100 mas pre-optic setting, and DIT=600. In the following examples */path\_raw/* indicates the full path to the source tree directory containing raw data.

Dark Frames: those frames are characterized by `DPR.TYPE='DARK'`,

```
/path_raw/DARK/600/SINFO.2004-08-23T09:36:12.316.fits DARK
/path_raw/DARK/600/SINFO.2004-08-23T09:51:59.824.fits DARK
/path_raw/DARK/600/SINFO.2004-08-23T10:07:40.760.fits DARK
```

Detector linearity flat field frames: those frames are characterized by `DPR.TYPE='LINEARITY,LAMP'`

<sup>6</sup>The procedure using *Gasgano* is conceptually identical.

<sup>7</sup>We omit here the prefix `HIERARCH ESO`

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```

/path_raw/LINEARITY/K/SINFO.2005-02-26T20:09:50.882.fits LINEARITY_LAMP
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:07.455.fits LINEARITY_LAMP
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:23.047.fits LINEARITY_LAMP
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:38.240.fits LINEARITY_LAMP
...
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:56.403.fits LINEARITY_LAMP
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:11:31.128.fits LINEARITY_LAMP
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:11:59.183.fits LINEARITY_LAMP
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:12:27.247.fits LINEARITY_LAMP

```

In case the user would like to use these frame with the new recipe **sinfo\_rec\_lingain** the tag to be used must also indicate if the lamp used to illuminate the detector was switched “on” or “off”, for example as in the following example:

```

/path_raw/LINEARITY/K/SINFO.2005-02-26T20:09:50.882.fits LINEARITY_LAMP_OFF
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:07.455.fits LINEARITY_LAMP_ON
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:23.047.fits LINEARITY_LAMP_ON
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:38.240.fits LINEARITY_LAMP_OFF
...
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:56.403.fits LINEARITY_LAMP_OFF
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:11:31.128.fits LINEARITY_LAMP_ON
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:11:59.183.fits LINEARITY_LAMP_ON
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:12:27.247.fits LINEARITY_LAMP_OFF

```

Fibre frames, flat frames and arc lamp frames to compute distortions: those frames have DPR.TYPE respectively equal to 'DISTORTION,FIBRE,NS' 'DISTORTION,FLAT,NS' (usually 2 frames, one with calibration flat lamp switched on, one with the lamp switched off), 'DISTORTION,WAVE,NS' .

```

/path_raw/DISTORTION/K/SINFO.2005-03-14T11:46:25.168.fits FIBRE_NS
/path_raw/DISTORTION/K/SINFO.2005-03-14T11:46:53.132.fits FIBRE_NS
/path_raw/DISTORTION/K/SINFO.2005-03-14T11:47:09.065.fits FIBRE_NS
/path_raw/DISTORTION/K/SINFO.2005-03-14T11:47:31.008.fits FIBRE_NS
/path_raw/DISTORTION/K/SINFO.2005-03-14T11:47:49.771.fits FIBRE_NS
.
.
/path_raw/DISTORTION/K/SINFO.2005-03-14T11:52:35.116.fits FIBRE_NS
/path_raw/DISTORTION/K/SINFO.2005-03-14T11:53:22.863.fits FLAT_NS
/path_raw/DISTORTION/K/SINFO.2005-03-14T11:53:45.397.fits FLAT_NS
/path_raw/DISTORTION/K/SINFO.2005-03-14T11:54:08.861.fits WAVE_NS
/path_raw/DISTORTION/K/SINFO.2005-03-14T11:55:10.220.fits WAVE_NS

```

Standard flat field frames: those frames are characterized by DPR.TYPE='FLAT,LAMP'

```

/path_raw/FLAT/K/100/SINFO.2005-02-28T16:27:43.232.fits FLAT_LAMP

```

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```

/path_raw/FLAT/K/100/SINFO.2005-02-28T16:28:05.846.fits FLAT_LAMP
/path_raw/FLAT/K/100/SINFO.2005-02-28T16:28:18.820.fits FLAT_LAMP
/path_raw/FLAT/K/100/SINFO.2005-02-28T16:28:32.593.fits FLAT_LAMP
/path_raw/FLAT/K/100/SINFO.2005-02-28T16:28:45.566.fits FLAT_LAMP
/path_raw/FLAT/K/100/SINFO.2005-02-28T16:29:08.165.fits FLAT_LAMP

```

Arc lamp frames: those frames are characterized by `DPR.TYPE='WAVE,LAMP'`

```

/path_raw/WAVE/K/100/SINFO.2005-02-28T17:55:44.753.fits WAVE_LAMP
/path_raw/WAVE/K/100/SINFO.2005-02-28T18:00:15.875.fits WAVE_LAMP

```

science frames: those frames are characterized by `DPR.TYPE='OBJECT'` or `DPR.TYPE='SKY'`

```

/path_raw/SCI/K/100/SINFO.2005-02-27T04:30:22.175.fits OBJECT_NODDING
/path_raw/SCI/K/100/SINFO.2005-02-27T04:30:54.620.fits SKY_NODDING
/path_raw/SCI/K/100/SINFO.2005-02-27T04:31:19.755.fits SKY_NODDING
/path_raw/SCI/K/100/SINFO.2005-02-27T04:31:46.369.fits OBJECT_NODDING
/path_raw/SCI/K/100/SINFO.2005-02-27T04:32:12.983.fits OBJECT_NODDING
/path_raw/SCI/K/100/SINFO.2005-02-27T04:32:46.418.fits SKY_NODDING

```

To have additional information on the instrument performance the user may want to reduce also telluric standard star frames: those frames are characterized by `DPR.TYPE='STD'` or `DPR.TYPE='SKY,STD'`

```

/path_raw/STD/K/100/SINFO.2005-02-27T09:17:05.775.fits STD
/path_raw/STD/K/100/SINFO.2005-02-27T09:18:10.566.fits SKY_STD

```

or PSF standard star frames: those frames are characterized by `DPR.TYPE='PSF-CALIBRATOR'` or `DPR.TYPE='SKY,PSF-CALIBRATOR'`

```

/path_raw/PSF/K/100/SINFO.2004-08-23T07:35:16.597.fits PSF_CALIBRATOR
/path_raw/PSF/K/100/SINFO.2004-08-23T07:36:55.413.fits SKY_PSF_CALIBRATOR

```

We describe below a typical data reduction sequence using EsoRex. In this section we assume that the user sets in the EsoRex configuration file (`$HOME/esorex/esorex.rc`) the flag *suppress-prefix* to `TRUE`, so that the pipeline product file names have standard names, with extension `.fits` for images and tables. We suggest to verify to have the flag *readonly* set to `FALSE`, if the user would like to run the same recipe several times with EsoRex having standard names for product files. This setting allows the pipeline to overwrite previously generated products<sup>8</sup>. In the following we indicate only those frames involved in the data reduction cascade, suggesting the user to rename them according to their `PRO.CATG`, `INS.SETUP.ID` and band, and to remove the other products after each recipe execution.

<sup>8</sup>By default installation in the EsoRex configuration file (`$HOME/esorex/esorex.rc`) the flag *suppress-prefix* to `FALSE` and the flag *readonly* is set to `FALSE`, a possible combination, in which case pipeline product filenames will have a prefix `out_`, an increasing a four digit number, and extension `.fits` for images and tables.

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1. The user may start to generate a master dark. Raw dark frames may be put in an ASCII file, `mdark_sof`. This file will look like as follows:

```
/path_raw/DARK/600/SINFO.2004-08-23T09:36:12.316.fits DARK
/path_raw/DARK/600/SINFO.2004-08-23T09:51:59.824.fits DARK
/path_raw/DARK/600/SINFO.2004-08-23T10:07:40.760.fits DARK
```

Then the user can generate the master dark with the command

**esorex sinfo\_rec\_mdark mdark\_sof**

This command will generate two files: `out_bp_noise.fits` (PRO.CATG=BP\_MAP\_HP), a hot pixel map, and `out_dark.fits` (PRO.CATG=MASTER\_DARK), a master dark. For convenience we indicate with `/path_cdb` the full path to a directory containing relevant data reduction products.

**mv out\_bp\_noise.fits /path\_pro/BP\_MAP\_HP.fits**

**mv out\_dark.fits /path\_pro/MASTER\_DARK\_600.fits**

**rm -rf out\*fits \*.paf \*.log**

It is possible to generate a master dark and a detector signal non uniformity (DSNU) map with the command

**esorex sinfo\_rec\_mdark\_detmon mdark\_sof**

This command will generate three files: `sinfo_rec_mdark_detmon_master_dit_1.fits`, a master dark frame (PRO.CATG=MASTER\_DARK), `sinfo_rec_mdark_detmon_dsnu_map_1.fits`, a DSNU image map (PRO.CATG=DSNU\_MAP), and `sinfo_rec_mdark_detmon_dsnu_table_1.fits`, a DSNU table (PRO.CATG=DSNU\_TABLE).

This recipe is being used for quality control and being tested for the reduction chain. We recommend the user not to use it in the usual reduction chain with this release.

**rm -rf out\*fits \*.paf \*.log**

2. Then the user may generate a map of non linear pixels. A set of linearity raw flat field frames may be put in the ASCII file `linearity_sof`.

```
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:09:50.882.fits LINEARITY_LAMP
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:07.455.fits LINEARITY_LAMP
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:23.047.fits LINEARITY_LAMP
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:38.240.fits LINEARITY_LAMP
...
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:56.403.fits LINEARITY_LAMP
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:11:31.128.fits LINEARITY_LAMP
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:11:59.183.fits LINEARITY_LAMP
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:12:27.247.fits LINEARITY_LAMP
```

The user can generate a non linearity bad pixel map (PRO.CATG=BP\_MAP\_NL) with the command:

**esorex sinfo\_rec\_detlin linearity\_sof**

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This command will generate several files, including the non linearity bad pixel map, stored in the file “out\_bp\_lin.fits”.

**mv out\_bp\_lin.fits /path\_pro/BP\_MAP\_NL\_K.fits**

**rm -rf out\*fits \*.paf \*.log**

3. Then the user may generate a map of non linear pixels and compute the detector’s gain by using the additional recipe `sinfo_rec_lingain`. A set of linearity raw flat field frames may be put in the ASCII file `lingain_sof`. As indicated below, despite those frame are the same input as in the `sinfo_rec_detlin` recipe, the tags should indicate also if the lamp used to illuminate the frame is “off” or “on” (the Halogen lamp status can be determined by the value of the FITS keyword `INS1.LAMP5.ST`). The user must provide at least 4\*(order+1) input frames: by default at least 16 frames.

```
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:09:50.882.fits LINEARITY_LAMP_OFF
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:07.455.fits LINEARITY_LAMP_ON
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:23.047.fits LINEARITY_LAMP_ON
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:38.240.fits LINEARITY_LAMP_OFF
...
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:10:56.403.fits LINEARITY_LAMP_OFF
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:11:31.128.fits LINEARITY_LAMP_ON
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:11:59.183.fits LINEARITY_LAMP_ON
/path_raw/LINEARITY/K/SINFO.2005-02-26T20:12:27.247.fits LINEARITY_LAMP_OFF
```

The user can generate a non linearity bad pixel map (`PRO.CATG=BP_MAP_NL`) with the command:

**esorex sinfo\_rec\_lingain lingain\_sof**

This command will generate several files: two tables, one (`sinfo_rec_lingain_linearity_table.fits`) including the non linearity information (`PRO.CATG=DET_LIN_INFO`), the other (`sinfo_rec_lingain_gain_table.fits`) including the detector’s gain information (`PRO.CATG=GAIN_INFO`), a 3D data product (`sinfo_rec_lingain_coeffs_cube.fits`) with the information on the pix-to-pix polynomial coefficients used to evaluate the detector’s linearity (`PRO.CATG=COEFFS_CUBE`), and (`sinfo_rec_lingain_bpm.fits`) a non linear pixel map (`PRO.CATG=BP_NL_MAP`).

This recipe is being used for quality control and being tested for the reduction chain. We recommend the user not to use it in the usual reduction chain with this release.

**rm -rf out\*fits \*.paf \*.log**

4. Then the user may determine the optical distortions (`PRO.CATG=DISTORTION`) and the slitlets distances (`PRO.CATG=SLITLETS_DISTANCE`).

The user will select all the files containing the string `DISTORTION` in their `DPR.TYPE`. Using those files and the line reference table of the corresponding band (K) and a `drs` setup table will generate an ASCII file `distortion_sof`:

```
/path_raw/SINFO.2005-03-14T11:28:19.007.fits FIBRE_NS
/path_raw/SINFO.2005-03-14T11:28:43.781.fits FIBRE_NS
/path_raw/SINFO.2005-03-14T11:28:59.723.fits FIBRE_NS
/path_raw/SINFO.2005-03-14T11:29:18.496.fits FIBRE_NS
.
```

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.

```

/path_raw/SINFO.2005-03-14T11:53:22.863.fits FLAT_NS
/path_raw/SINFO.2005-03-14T11:53:45.397.fits FLAT_NS
/path_raw/SINFO.2005-03-14T11:54:08.861.fits WAVE_NS
/path_raw/SINFO.2005-03-14T11:55:10.220.fits WAVE_NS
/path_cdb/neonK.fits REF_LINE_ARC
/path_cdb/drs_setup_wave.fits DRS_SETUP_WAVE

```

To successfully run the distortion recipe are needed: several (usually 75) FIBRE\_NS frames, needed to cover all slitlets and generate an uniformly illuminated synthetic fibre flat; two FLAT\_NS frames, one with calibration flat lamp switched on, one with the lamp switched off; two WAVE\_LAMP frames, one with calibration flat lamp switched on, one with the lamp switched off; and the two static frames, the reference line list of the appropriate band, with tag REF\_LINE\_ARC, and the static parameters table with tag DRS\_SETUP\_WAVE as indicated above.

Where with /path\_cdb we have indicated the full path to the directory containing calibration data. REF\_LINE\_ARC is the file TAG (PRO.CATG) assigned to the frame table containing the reference line list to be used to perform the wavelength calibration and DRS\_SETUP\_WAVE is an additional reference table storing instrument setting dependent parameters, which are expected to be stable, used during the wavelength calibration (see also Sec. 8). The command

#### **esorex sinfo\_rec\_distortion distortion\_sof**

Will generate several products. Between those also out\_distortion.fits, a table containing information on the polynomial distortion coefficients, and out\_distances.fits, a table containing information on the slitlet distances.

**mv out\_distortion.fits /path\_pro/DISTORTION\_K.fits**

**mv out\_distances.fits /path\_pro/SLITLETS\_DISTANCE\_K.fits**

**rm -rf out\*fits \*.paf \*.log**

5. Then one selects the raw flat fields and list them in an ASCII file mflat\_sof together with some static calibrations and previously obtained products:

```

/path_raw/FLAT/SINFO.2005-02-28T16:27:43.232.fits FLAT_LAMP
/path_raw/FLAT/SINFO.2005-02-28T16:28:05.846.fits FLAT_LAMP
/path_raw/FLAT/SINFO.2005-02-28T16:28:18.820.fits FLAT_LAMP
/path_raw/FLAT/SINFO.2005-02-28T16:28:32.593.fits FLAT_LAMP
/path_raw/FLAT/SINFO.2005-02-28T16:28:45.566.fits FLAT_LAMP
/path_raw/FLAT/SINFO.2005-02-28T16:29:08.165.fits FLAT_LAMP
/path_cdb/REF_BP_MAP.fits REF_BP_MAP
/path_pro/BP_MAP_NL_K.fits BP_MAP_NL

```

The frame REF\_BP\_MAP is an image indicating reference positions of known detector bad pixels (see also Sec 8).

The command:



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#### **esorex sinfo\_rec\_mflat mflat\_sof**

generates several frames, including the master flat field, stored in the file “out\_flat.fits”, and the master bad pixel map, stored in the file “out\_bpmmap\_sum.fits”.

**mv out\_flat.fits /path\_pro/MASTER\_FLAT\_LAMP\_K\_100.fits**

**mv out\_bpmmap\_sum.fits /path\_pro/MASTER\_BP\_MAP\_K\_100.fits**

**rm -rf out\*fits \*.paf \*.log**

6. Then one lists raw arc lamp frames and additional static calibration frames and previously obtained master calibrations in an ASCII file wcal\_sof:

```
/path_raw/WAVE/SINFO.2005-02-28T17:55:44.753.fits WAVE_LAMP
/path_raw/WAVE/SINFO.2005-02-28T18:00:15.875.fits WAVE_LAMP
/path_cdb/neonK.fits REF_LINE_ARC
/path_pro/MASTER_FLAT_LAMP_K_100.fits MASTER_FLAT_LAMP
/path_pro/MASTER_BP_MAP_K_100.fits MASTER_BP_MAP
/path_pro/DISTORTION_K.fits DISTORTION
/path_cdb/drs_setup_wave.fits DRS_SETUP_WAVE
/path_cdb/SLIT_POS_K_100.fits SLIT_POS
```

The command:

#### **esorex sinfo\_rec\_wavecal wcal\_sof**

generates several frames, including the master wavelength map, stored in the file “out\_wavemap\_ima.fits”, and the slitlet position table, stored in the file “out\_slitpos.fits”.

**mv out\_wavemap\_ima.fits /path\_pro/MASTER\_WAVE\_MAP\_K\_100.fits**

**mv out\_slitpos.fits /path\_pro/SLIT\_POS\_K\_100.fits**

**rm -rf out\*fits \*.paf \*.log**

7. Finally the user will reduce the science data:

```
/path_raw/OBJNOD/SINFO.2005-02-27T06:09:19.358.fits OBJECT_NODDING
/path_raw/OBJNOD/SINFO.2005-02-27T06:10:10.996.fits SKY_NODDING
/path_raw/OBJNOD/SINFO.2005-02-27T06:11:33.949.fits OBJECT_NODDING
/path_raw/OBJNOD/SINFO.2005-02-27T06:13:08.204.fits SKY_NODDING
/path_raw/OBJNOD/SINFO.2005-02-27T06:14:40.068.fits OBJECT_NODDING
/path_raw/OBJNOD/SINFO.2005-02-27T06:16:11.122.fits SKY_NODDING
/path_pro/MASTER_BP_MAP_K_100.fits MASTER_BP_MAP
/path_pro/MASTER_FLAT_LAMP_K_100.fits MASTER_FLAT_LAMP
/path_pro/WAVE_MAP_K_100.fits WAVE_MAP
/path_pro/SLITLETS_DISTANCE_K.fits SLITLETS_DISTANCE
/path_pro/SLIT_POS_K_100.fits SLIT_POS
/path_pro/DISTORTION_K.fits DISTORTION
```



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The command:

**esorex sinfo\_rec\_jitter sci\_sof**

generates several frames, including a reconstructed cube of the PSF standard, stored in the file “out\_cube\_obj##.fits” (##=00,01,..NN), its median image, stored in the file “out\_objnod\_med\_cube.fits”, the associated bad pixel map, stored in the file “out\_objnod\_bmap.fits”, a table with Strehl values as a function of wavelength, stored in the file “out\_ao\_performance.fits”, a table with encircled energy values, stored in the file “out\_encircled\_energy.fits”. A table with the extracted average object spectrum, stored in the file “out\_std\_star\_spectrum.fits”. We remind the user to read section [11.1.26](#) for important information on how to obtain the best quality of sky subtracted object spectra.

8. If the user is interested to find information on the efficiency of the detector, it is necessary to reduce standard star calibrations. This can be done collecting appropriate data in a stdstar\_sof file:

```
/path_raw/STD/SINFO.2005-02-27T06:09:19.358.fits STD
/path_raw/STD/SINFO.2005-02-27T06:10:10.996.fits SKY_STD
/path_pro/MASTER_BP_MAP_K_100.fits MASTER_BP_MAP
/path_pro/MASTER_FLAT_LAMP_K_100.fits MASTER_FLAT_LAMP
/path_pro/WAVE_MAP_K_100.fits WAVE_MAP
/path_pro/SLITLETS_DISTANCE_K.fits SLITLETS_DISTANCE
/path_pro/SLIT_POS_K.fits SLIT_POS
/path_pro/DISTORTION_K.fits DISTORTION
```

The command:

**esorex sinfo\_rec\_jitter stdstar\_sof**

generates several frames, including a reconstructed cube of the telluric standard, stored in the file “out\_cube\_obj##.fits” (##=00,01,..NN), its median image, stored in the file “out\_objnod\_med\_cube.fits”, the associated bad pixel map, stored in the file “out\_objnod\_bmap.fits”, a table with Strehl values as a function of wavelength, stored in the file “out\_ao\_performance.fits”, a table with encircled energy values, stored in the file “out\_encircled\_energy.fits”. A table with the extracted average object spectrum, stored in the file “out\_std\_star\_spectrum.fits”.

9. If the user is interested to find information on the Strehl, it is necessary to reduce PSF standard frames. This can be done collecting appropriate data in a psf\_sof file:

```
/path_raw/PSF/SINFO.2005-02-27T06:09:19.358.fits PSF_CALIBRATOR
/path_raw/PSF/SINFO.2005-02-27T06:10:10.996.fits SKY_PSF_CALIBRATOR
/path_pro/MASTER_BP_MAP_K_100.fits MASTER_BP_MAP
/path_pro/MASTER_FLAT_LAMP_K_100.fits MASTER_FLAT_LAMP
/path_pro/WAVE_MAP_K_100.fits WAVE_MAP
/path_pro/SLITLETS_DISTANCE_K_100.fits SLITLETS_DISTANCE
/path_pro/SLIT_POS_K_100.fits SLIT_POS
/path_pro/DISTORTION_K.fits DISTORTION
```

The command:

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### **esorex sinfo\_rec\_jitter psf\_sof**

generates several frames, including a reconstructed cube of each target observation, stored in the file “out\_cube\_obj##.fits” (##=00,01,..NN), (##=00-01-NN), a mosaic cube coadding each single cube observation, stored in the file “out\_objnod.fits” its median image, stored in the file “out\_objnod\_med\_cube.fits”, the associated bad pixel map, stored in the file “out\_objnod\_bpmmap.fits”, and for poiint-like target observations (for objects whose PSF can well approximated by a 2D Gaussian), a table with Strehl values as a function of wavelength, stored in the file “out\_ao\_performance.fits”, a table with encircled energy values, stored in the file “out\_encircled\_energy.fits”. A table with the extracted average object spectrum, stored in the file “out\_std\_star\_spectrum.fits”.

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## 6 Known problems

We suggest the user to execute the data reduction recipes using parameter defaults and all the reference and master calibrations indicated in this manual. The following is a list of currently-known issues with SINFONI recipes, and workarounds, if available:

Some user has reported that occasionally recipes may fail with error message “Error code -1”, that is not very clear. That message is conventional, and the last message of the error stack. We invite the user to check the full error stack: usually the real source of the problem is shown by some other error messages on the error stack.

Bad lines present on long exposure frames. This problem, visible for example on dark frames, is introduced by the data processing hardcoded at detector level. The four pixels surrounding the detector are not illuminated and are used by the hardcoded processing to estimate the “bias” level for each frame. The mean of each line is then subtracted from the frame prior to write the data onto the instrument workstation. When one of this hot pixel is located among the non illuminated “edge” pixels, the mean value of the corresponding line is then over-estimated, which creates some dark stripes in the raw frames when it is subtracted. This defect can be corrected using the utility `sinfo_utl_ima_line_corr`, or setting to “TRUE” the relevant recipes common parameter **lc\_sw**.

**sinfo\_rec\_detlin** . LINEARITY,LAMP data taken in the period 24/11/2006-28/02/2007 have been taken with increased lamp intensities. This means that in particular frames taken with high values of DET.DIT (for example DET.DIT=45) have several pixels in the non linear detector’s range. This affects particularly the J band. As a consequence if the user uses recipe parameter defaults may obtain non linear pixel maps (ESO.PRO.CATG=BP\_MAP\_NL) collecting significantly more pixels than usual, and this would propagate in the MASTER\_BP\_MAP. Those pixels consequently would not be taken in consideration in the calibration, despite the level of the signal in the arc lamp frames is in the linear regime, this possibly leading to a lower quality WAVE\_MAP and wavelength calibration solution. To solve this problem the user may:

- Not use raw frames at higher DET.DIT to build the non linear bad pixel map.
- Use all the raw frames and increase the parameter **bp\_lin-thresh\_sigma\_fct** from the default 10 to 15 or more.

**sinfo\_rec\_distortion** Occasionally this recipe may fail indicating that too less slitlets have been found. The user may try to increase the parameter **smooth\_rad** or the parameter **arcs\_min\_arclen\_factor**.

**sinfo\_rec\_wavecal** This recipe sometimes fails to determine the positions of the slitlets. A possible reason is an improper data reduction parameter setting. For example the parameter **wcal-pixel\_tol** has a default value of 3.0 to insure good accuracy. Values equal to 5 or 6 may insure higher robustness at the price of a minor accuracy. Another parameter to eventually change to improve robustness is **wcal-pixel\_dist**. It has a default value of 12. One may try to increase it a bit, for example to 15. The same is true for the parameters having aliases **wcal-min\_diff**, **wcal-na\_coeffs**, **wcal-nb\_coeffs**, **wcal-pix\_tol**, **wcal-y\_box**, which in the current release, for accuracy, have default values as specified in the first column of the following table but in previous releases they had default values as specified in the other table rows, values which might offer greater robustness at a price of a minor accuracy.

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band	wcal-min_diff	wcal-na_coeffs	wcal-nb_coeffs	wcal-pix_tol	wcal-y_box	comment
any	1.0	4	2	3.0	5.0	default setting
H	10.0	3	2	7.0	2.0	old setting
H+K	1.0	4	2	5.5	5.0	old setting
K	1.0	4	2	12.0	5.0	old setting
J	1.0	4	2	3.0	5.0	old setting

Another possible explanation of the failure is the usage of an improper bad pixel map. We suggest to use the REF\_BP\_MAP, provided with the present kit release, as input of the `sinfo_rec_mflat` recipe which determines the MASTER\_BP\_MAP, which is input of the `sinfo_ref_wavecal` recipe.

**sinfo\_rec\_jitter** Sky subtraction quality. Despite we provide an improved routine to correct for possible sky line residuals, we suggest the user to use it only when (at least) a sky frame is available. Otherwise (if the user uses such correction in absence of a sky frame, case in which the next in time object frame is used as “dummy” sky), there is the risk that object lines cancel out after subtraction. The user should also choose proper values of the critical parameters **skycor-sky\_bkg\_filter\_width**, **skycor-line\_hw**, **skycor-rot\_cor**, **skycor-fit\_obj\_noise**.

This release allows also to indicate the area where is supposed to be imaged the object, through the parameters **skycor-llx**, **skycor-lly**, **skycor-urx**, **skycor-ury**, which should allow a more accurate determination of the sky lines residuals and the corresponding spectrum shift with respect to the one of the object. The thermal background emission subtraction can be eventually switched off with the parameter **skycor-sub\_thr\_bkg\_from\_obj**. If the user has estimated the sky-object spectral shift independently, or would like to overwrite the value computed by the pipeline, can set this quantity (in pixel units) with the parameter **skycor-pshift**.

A check of the results provided by the product table(s) with PRO.CATG QC\_SPECTRA is always recommended to compare the extracted spectra before and after the correction.

**sinfo\_rec\_jitter** WCS coordinates in the coadded cube may be inaccurate. We invite the user to check the accuracy of the reference catalog used, it may be that the VLT-SINFONI combo is more accurate; eventually correct object coordinate to take into account of its possible proper motion.

**sinfo\_rec\_jitter** Seldomly, this recipe may originate coadded cubes whose spectra along z axis may have spikes. This occurrence may be an indication that the the kappa sigma clipping has removed some object point. In those cases we suggest to increase the value of kappa.

**sinfo\_rec\_jitter** Some user may have observations taken with the telescope position angle not equal to 0. This occurrence can be revealed verifying that the value of the FITS keyword ADA\_POSANG is not 0. In those cases the pipeline may coadd several cubes components incorrectly. In those cases we suggest the user to use **sinfo\_utl\_coadd\_combine** and provide proper offsets. See also section 10.16.

**sinfo\_rec\_jitter** This recipe may fail to perform a 2D Gaussian fit to the observed target. In this case the STD\_STAR\_SPECTRA and STD\_STAR\_SPECTRUM pipeline products will not be generated. The user may try to reduce the value of the parameter **std\_star-fwhm\_factor** to get also those products.

**sinfo\_rec\_jitter** Has performance limits. The fastest execution may be obtained setting **product-density** to 0.

**sinfo\_rec\_jitter** This recipe is much demanding in term of RAM. The amount of RAM required is approximately given by the formula:

$$\text{RAM} = [150 + 4 \times (2 \times sX \times sY \times sZ + 64 \times 64 \times sZ \times N_{frames}) \times 10^{-6}] \text{ MB},$$

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where  $sX$ ,  $sY$ ,  $sZ$  indicate the size of the coadded cube and  $N_{frames}$  is the number of coadded cubes.  $sX$  and  $sY$  are a function of the minimum and maximum x and y offsets of the coadded cube components with respect to the first one:

$$sX = 2 \times \text{floor}(\text{off}x_{max} - \text{off}x_{min} + 0.5) + 64 \quad sY = 2 \times \text{floor}(\text{off}y_{max} - \text{off}y_{min} + 0.5) + 64$$

The  $\text{floor}(x)$  function computes the largest integral value not greater than  $x$ . We suggest the user to have at least 1GB of RAM and a swap area at least equal to the amount of RAM. In case,  $sX = sY = 130$ ,  $sZ = 2300$ ,  $N_{frames} = 30$ , the user needs at least 1.6 GB of RAM, the same amount of swap, dedicated to run the pipeline. We also suggest the user to check before starting the data reduction the values of keywords SEQ CUMOFFSETX and SEQ CUMOFFSETY. Sometimes those may be very different. This may be such that the size of the output coadded cube is large enough not to allow a full data reduction, due to the limited amount of available RAM.

In those cases, or if the single cube components correspond to observations of portions of the sky which do not overlap with each other, we suggest the user to set **objnod-jit\_ind=FALSE**.

EsoRex may report at the end of a recipe execution the following wrong information:

```
[ INFO ] esorex: (no ESO PRO CATG keyword found...)
```

The user should ignore it, the SINFONI pipeline products have the ESO.PRO.CATG keyword properly set.

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## 7 Instrument Data Description

SINFONI data reduction often involves pair of frames: calibrations in which an “on” frame is acquired with a calibration lamp switched on and an “off” frame recorded with the same lamp switched off, or observations of science objects and of the sky background. Additionally, dark frames are taken as well as special fibre flat frames used to compute optical distortions. Fibre flats are taken with the calibration fibre moved along the y-axis perpendicular to the image slices. Due to a non uniform illumination of a small number of slitlets from the fibre link, several raw frames (usually 75) are necessary to build a synthetic all-slitlets fibre fed flat needed to compute the optical distortions. Each kind of raw frame is typically associated to a single SINFONI pipeline recipe, *i.e.*, the recipe assigned to the reduction of that specific frame type. In the pipeline environment this recipe would be executed automatically. The recipe to compute optical distortions takes as input several kinds of raw frames, including flats in which a few instrument slitlets are illuminated by a fibre, and standard pairs of flat field and arc lamp frames.

In the following sections after a brief description of how most of the raw data look like, all raw SINFONI data frames are listed, together with the keywords used for their classification and correct association. The indicated *DO category* is a label assigned to any data type after it has been classified, which is then used to identify the frames listed in the *Set of Frames* (see Section 5.2.2, page 24). We also provide snapshots of each of the main raw data “on” frames (“off” frames snapshots are not provided as they usually look like dark frames).

### 7.1 Data features

In figure 7.1.1 we have represented how a possible observation target, (*a*), is imaged on the detector, (*b*). The 32 input source’s slices generated by the two image slicers are imaged on the detector. These are also called slitlets and appear as vertical strips. Each slitlet has two edges, which can be seen by looking at the horizontal traces of sky emission lines or atmospheric absorption from the hydroxyl molecule OH. Those lines also show that the slitlets are arranged in a brick-wall pattern, to ease the detection of their edges, and that the first slitlet has a left edge not coincident with the left border of the detector. The detector column corresponding to this edge is called first column and it is taken as reference to measure the other 31 slitlets’ distances. This information, together with the actual position of each slitlet edge is necessary to reconstruct the input FOV image. The detector has a number of bad pixels and a circular defect near its center. The spatial information (both X and Y directions on the sky) is distributed along the horizontal direction alone (the X sky coordinate in each slitlet and the Y sky coordinate in the different slitlets) while the wavelength information is along the vertical direction, increasing downwards. The signal from a point-like object in the FOV with a finite PSF appears as a vertical stripe in each slitlet where its emission is relevant and it is superimposed on the sky background, more uniform along the spatial direction except in coincidence of emission lines visible as horizontal bright stripes. During an exposure the detector can be hit by cosmic rays.

In figure 7.1.2 we have the central plane of a coadded cube resulting from several target acquisitions observed at different telescope positions.

In figure 7.2.1 we have several examples of raw calibration and science frames.



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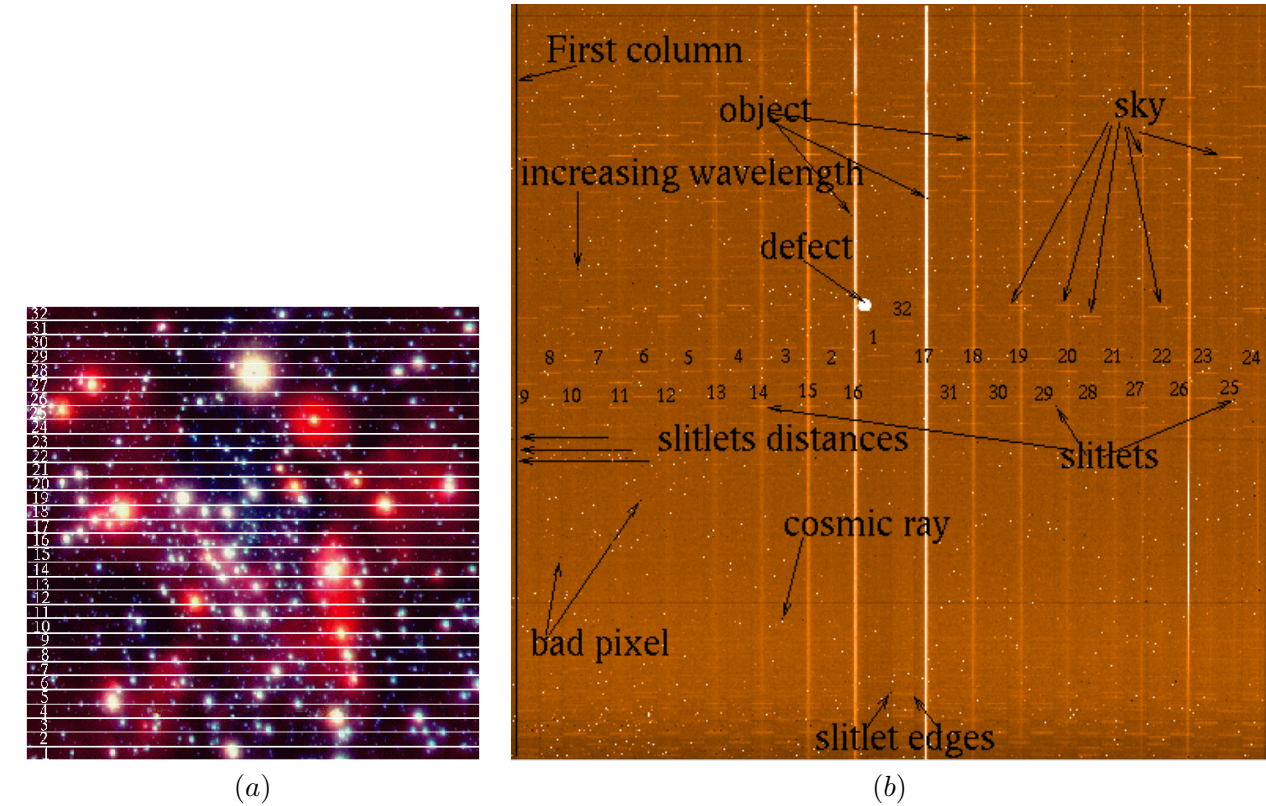


Figure 7.1.1: A possible target for observation (a) and a typical raw science frame layout (b).

## 7.2 Raw frames

We list in this section all raw frames with the relevant FITS keywords (omitting the prefix HIERARCH ESO) needed to classify them and associate to them the required calibration frames. Figure 7.2.1 shows the typical appearance of those frames.

- **Dark current:**

DO category: DARK  
Processed by: `sinfo_rec_mdark`

Classification keywords:  
DPR CATG = CALIB  
DPR TYPE = DARK  
DPR TECH = IMAGE

Association keywords:      Fig:  
DET DIT                      7.2.1 (a)

- **Flat Field:**

DO category: FLAT\_LAMP  
Processed by: `sinfo_rec_mflat`

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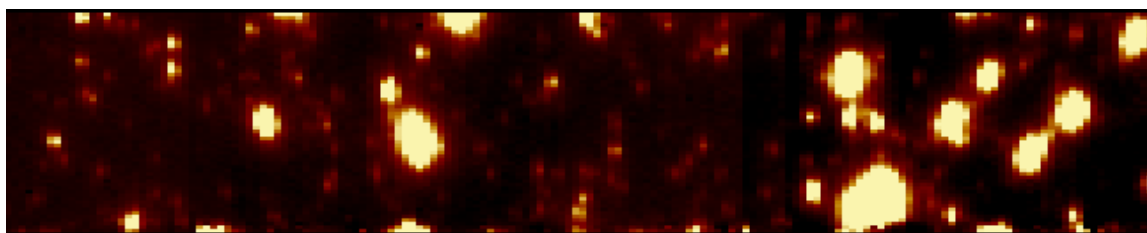


Figure 7.1.2: A coadded cube resulting from several “mosaiced” cubes.

**Classification keywords:**

DPR CATG = CALIB  
DPR TYPE = FLAT, LAMP  
DPR TECH = IFU

**Association keywords:**

INS SETUP ID  
INS OPT11 NAME

**Fig:**

[7.2.1](#) (b)

• **Detector linearity Flat Field:**

DO category: LINERITY\_LAMP

Processed by: sinfo\_rec\_detlin

**Classification keywords:**

DPR CATG = CALIB  
DPR TYPE = LINEARITY, LAMP  
DPR TECH = IFU

**Association keywords:**

INS SETUP ID  
INS1.LAMP5.ST

**Fig:**

[7.2.1](#) (b)

• **Detector-monitoring linearity Flat Field:**

DO category: LINERITY\_LAMP\_ON/OFF

Processed by: sinfo\_rec\_lingain

**Classification keywords:**

DPR CATG = CALIB  
DPR TYPE = LINEARITY, LAMP, DETCHAR  
DPR TECH = IFU

**Association keywords:**

INS SETUP ID  
INS1 LAMP5 ST

**Fig:**

[7.2.1](#) (b)

• **Flat field frames to compute distortions:**

DO category: FLAT\_NS

Processed by: sinfo\_rec\_distortion

**Classification keywords:**

DPR CATG = CALIB  
DPR TYPE = DISTORTION, FLAT, LAMP  
DPR TECH = IFU

**Association keywords:**

INS SETUP ID

**Fig:**

[7.2.1](#) (c)



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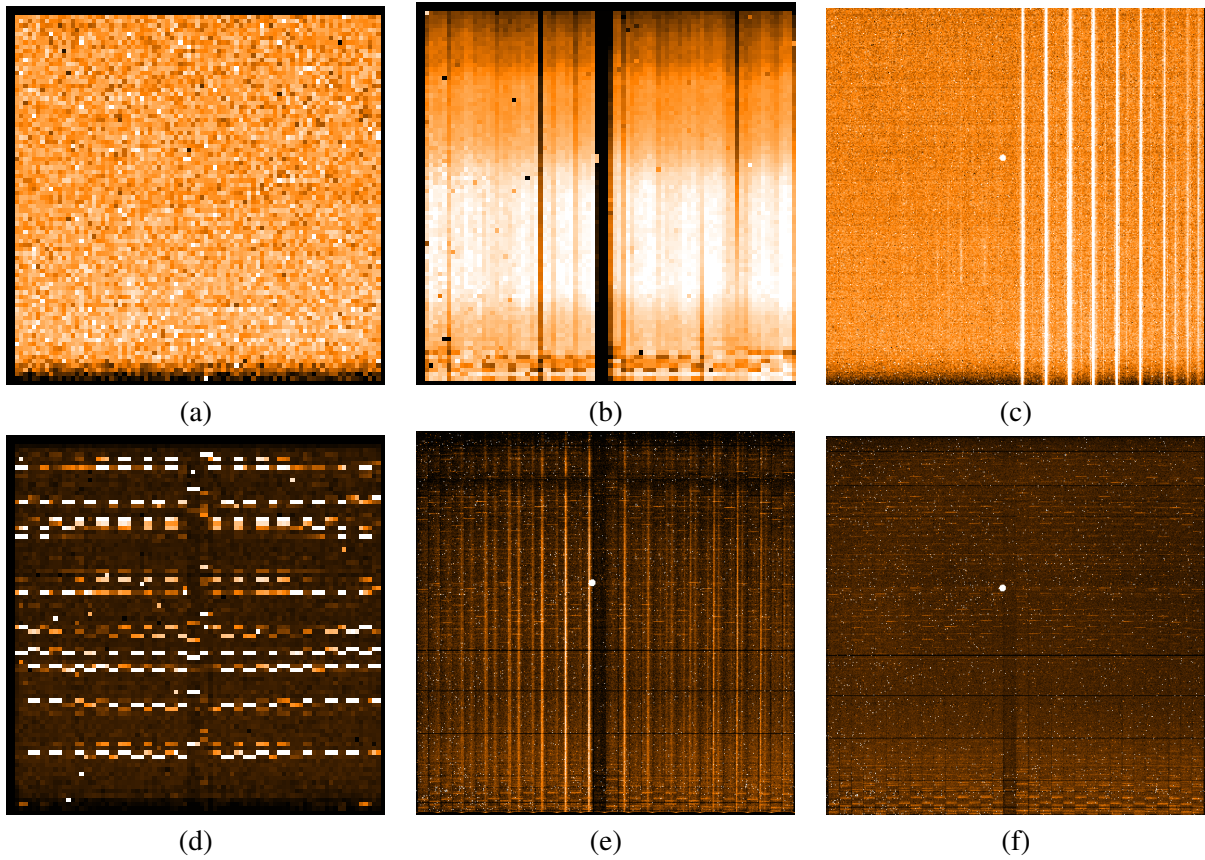


Figure 7.2.1: (a) a raw dark frame with DIT=1; (b) a flat field on in band H, 100mas; (c) a raw frame used to compute optical distortions; (d) an arc lamp on frame; (e) a science frame; (f) a sky frame.

• **Arc frames frames to compute distortions:**

DO category: WAVE\_NS  
 Processed by: sinfo\_rec\_distortion

Classification keywords:  
 DPR CATG = CALIB  
 DPR TYPE = DISTORTION, WAVE, LAMP  
 DPR TECH = IFU

Association keywords: INS SETUP ID  
 Fig: 7.2.1 (d)

• **Arc frames:**

DO category: WAVE\_LAMP  
 Processed by: sinfo\_rec\_wavecal

Classification keywords: DPR CATG = CALIB  
 Association keywords: INS SETUP ID  
 Fig: 7.2.1 (d)

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DPR TYPE = WAVE, LAMP  
DPR TECH = IFU

INS OPTI1 NAME

- **STD PSF star frames:**

DO category: PSF\_CALIBRATOR  
Processed by: sinfo\_rec\_psf

Classification keywords:  
DPR CATG = CALIB  
DPR TYPE = PSF-CALIBRATOR  
DPR TECH = IFU

Association keywords:  
INS SETUP ID  
INS OPTI1 NAME

Fig:  
[7.2.1 \(e\)](#)

- **Sky frames taken with STD PSF star frames:**

DO category: SKY\_PSF\_CALIBRATOR  
Processed by: sinfo\_rec\_jitter

Classification keywords:  
DPR CATG = CALIB  
DPR TYPE = SKY, PSF-CALIBRATOR  
DPR TECH = IFU

Association keywords:  
INS SETUP ID  
INS OPTI1 NAME

Fig:  
[7.2.1 \(f\)](#)

- **STD star frames:**

DO category: STD  
Processed by: sinfo\_rec\_jitter

Classification keywords:  
DPR CATG = CALIB  
DPR TYPE = STD  
DPR TECH = IFU

Association keywords:  
INS SETUP ID  
INS OPTI1 NAME

Fig:  
[7.2.1 \(e\)](#)

- **Sky frames taken with STD star frames:**

DO category: SKY\_STD  
Processed by: sinfo\_rec\_jitter

Classification keywords:  
DPR CATG = CALIB  
DPR TYPE = SKY, STD  
DPR TECH = IFU

Association keywords:  
INS SETUP ID  
INS OPTI1 NAME

Fig:  
[7.2.1 \(f\)](#)

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- **Science frames:**

DO category: OBJECT\_NODDING  
 Processed by: sinfo\_rec\_jitter

Classification keywords:	Association keywords:	Fig:
DPR CATG = SCIENCE	INS SETUP ID	<a href="#">7.2.1 (e)</a>
DPR TYPE = OBJECT	INS OPTI1 NAME	
DPR TECH = IFU,NODDING		

- **Sky frames taken with science frames:**

DO category: SKY\_NODDING  
 Processed by: sinfo\_rec\_jitter

Classification keywords:	Association keywords:	Fig:
DPR CATG = SCIENCE	INS SETUP ID	<a href="#">7.2.1 (f)</a>
DPR TYPE = SKY	INS OPTI1 NAME	
DPR TECH = IFU,NODDING		

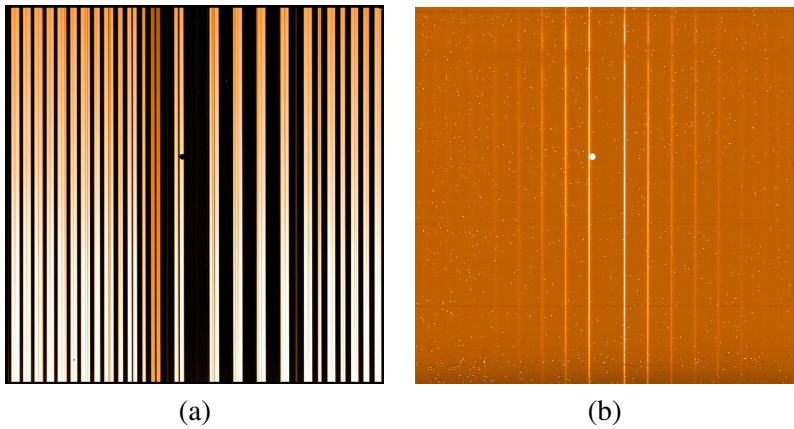


Figure 7.2.2: On-lamp raw data example for (a) PUPIL,IMAGE and (b) PRE,IMAGE data.

- **PUPIL,IMAGE frames:**

DO category: PUPIL\_IMAGE  
 Processed by: sinfo\_rec\_pupil

Classification keywords:	Association keywords:	Fig:
DPR CATG = CALIB	INS SETUP ID	<a href="#">7.2.2 (a)</a>
DPR TYPE = PUPIL, IMAGE	INS OPTI1 NAME	
DPR TECH = IFU,NODDING		

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- **PRE,IMAGE frames:**

DO category: PRE\_IMAGE

Processed by: sinfo\_rec\_jitter

**Classification keywords:**

DPR CATG = SCIENCE

DPR TYPE = OBJECT

DPR TECH = PRE, IMAGE

**Association keywords:**

INS SETUP ID

INS OPTI1 NAME

**Fig:**

[7.2.2](#) (b)

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## 8 Static Calibration Data

In the following section ancillary data required for SINFONI data reduction are listed. For each of them we indicate the corresponding value of the HIERARCH ESO PRO CATG, in short PRO.CATG, FITS keyword. This has to be used to identify the frames listed in the *Set of Frames* (see Section 5.2.2, page 24).

### 8.1 Line reference table

A reference list of arc lines is necessary to perform the wavelength calibration. Its PRO.CATG is REF\_LINE\_ARC. This frame is an input of the recipe `sinfo_rec_distortion` and `sinfo_rec_wavecal`.

### 8.2 DRS setup table

There are a few data reduction parameters which are band dependent and are supposed not to change. Those are collected in a table having PRO.CATG DRS\_SETUP\_WAVE. This frame is an input of the recipes `sinfo_rec_distortion` and `sinfo_rec_wavecal`.

band	W_START	W_DISP1	W_DISP2	W_HW	W_FWHM	W_MIN_AMP	W_LOW_POS	W_HI_POS
H	1.65	-2.00018796022e-4	9.3034524287e-10	7	2.83	5	750	1000
H+K	1.95	-5.001433e-4	4.567277e-9	8	3.00	2	1100	1260
K	2.20	-2.51669e-4	1.77136e-9	4	2.00	1	760	900
J	1.25	-1.500581e-4	5.8870678e-10	8	2.00	2	980	1175

This table set the values for data reduction parameters which in section 11 are respectively called **begin\_wave**, **guess\_disp1**, **guess\_disp2**, **half\_width**, **fwhm**, **min\_amp**, **lo\_pos**, **hi\_pos**. To change the values of such data reduction parameter, the user must edit this table.

### 8.3 Reference bad pixel map

Detector defects are logged as bad pixels in a special mask having PRO.CATG REF\_BP\_MAP. This is an input of the recipe `sinfo_rec_mflat`.

### 8.4 Reference table with flux of STD star for efficiency computation

To compute the efficiency, the user must provide a FITS table containing at least the two columns “WAVELENGTH” (in Angstrom units) and “FLUX” (in units of  $ergs \cdot cm^{-2} \cdot s^{-1} \cdot \text{\AA}^{-1}$ ) describing the analyzed standard star flux calibrated spectrum. This table has to be tagged as FLUX\_STD\_TABLE.

### 8.5 Reference tables with polynomial coefficients for correction due atmospheric refraction

The coefficients of the 2D polynomial fit for the correction due atmospheric refraction (see section 11.1.30 for more details), are saved into calibration tables (for example `ATM_REF_CORR_025_H.poly.fits`, for the 25mas H band setting and similar tables for the other settings. In the 250mas setting this correction is not offered as this spatial setting is more complex to calibrate and less affected by atmospheric refraction).

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## 9 Data Reduction

In this section, after an overview of the main problems the data reduction needs to solve, we list the required data and the recipes which allow to solve them, giving the data reduction sequence necessary to reduce calibration and science data.

### 9.1 Data reduction overview

The principle of integral field spectroscopy is described by figure [9.1.1](#). A two-dimensional image of the sky is separated by an image slicer into several components. Those are then aligned on a slit and dispersed to separate its spectral information and then imaged on a detector. The main SINFONI data reduction problems to solve are the following.

- Correct for the detector signature: bad pixels, detector contribution to the measured signal, flat fielding (correct pixel to pixel gain variations and relative slitlet throughput differences), correct geometric distortions.
- Perform the wavelength calibration.
- Reconstruct the image FOV from the 32 image slices in a format which contains both the spatial and the spectral information.
- Devise proper calibrations and observations to be able to properly correct the emission from the sky, from the instrument and from the telescope which are very strong in the NIR. This requires to take sky frames together with the object frames in the night observations, daily calibrations with the flat lamp switched on and off, and possibly dark frames.

In the following description we also indicate in parenthesis for each frame the corresponding PRO.CATG. To locate the detector bad pixels one uses a bad pixel map. A master bad pixel map resulting from the combination of a set of (different) bad pixel maps is generated by the master flat recipe. First of all, as the detector is known to have construction defects, these will be indicated by a reference bad pixel map (REF\_BP\_MAP). Hot pixels will be determined on dark frames (BP\_MAP\_HP). Non-linear response pixels are instead indicated by a bad pixel map (BP\_MAP\_NL) obtained by evaluating the pixel response of a set of flat exposures of increasing intensity. Other bad pixels (BP\_MAP\_NO) are determined on a set of flat fields (on the master flat field).

A master flat field (MASTER\_FLAT\_LAMP) generated from a set of raw flat fields, is used to correct the different detector pixel sensitivities. It is known that the image sliced and projected on the detector is affected by distortions. The `sinfo_rec_distortion` recipe computes the distortions (DISTORTION) and the slitlet distances (SLITLETS\_DISTANCE). It uses a set of raw frames where only the first column of each slitlet is illuminated through fibres. In addition flats and arcs are taken within the north south template as required to reduce the data. A set of “on” and “off” arc lamp frames, a reference line table, a master flat field, the optical distortions map and a good guess of the slitlet positions are input of the `wavecal` recipe. This recipe determines a wavelength map and obtains a better computation of the left edge position of each slitlet. From release 1.9.8 the user may also perform an OH lines based wavelength calibration on sky frames (see [10.7.1](#)).

Science (or PSF or telluric standard) frames are corrected for sky background, flat field, distortions, and calibrated in wavelength. The sorted slitlets are then stacked in a cube, taking into account the relative distances

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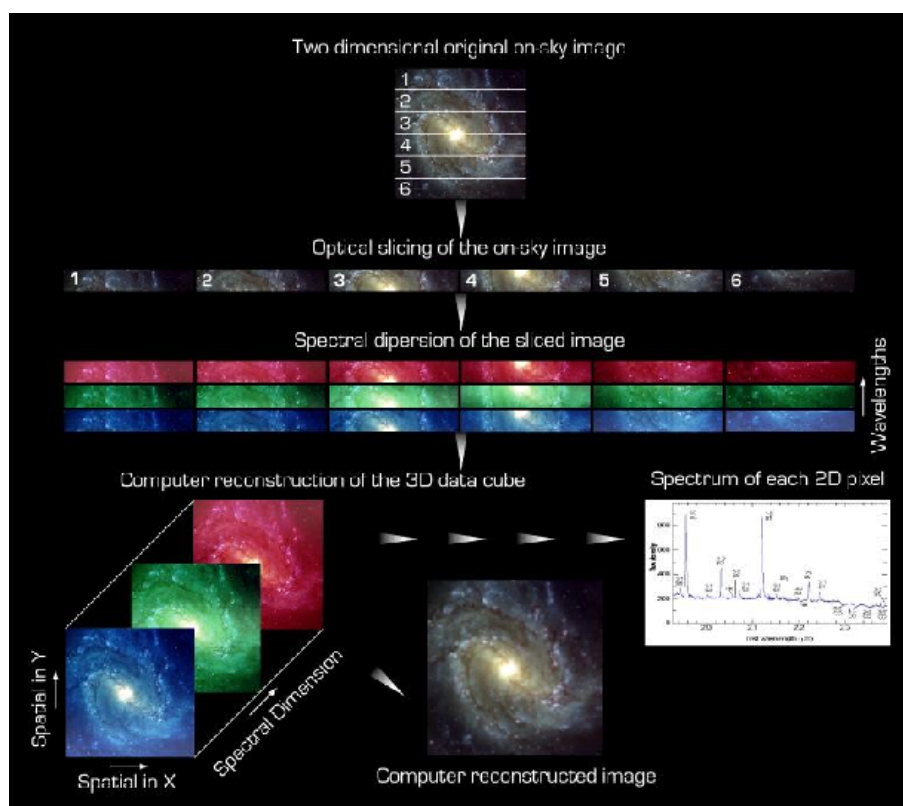


Figure 9.1.1: Integral Field Spectroscopy data reduction principle

of the position of the edge of each slitlet to the one of the first slitlet, with a final image realignment to get sub pixel accuracy. The final product is thus a 3D data cube where the full spatial information is stored along the X and Y directions, and the wavelength information is stored along the Z direction. Each plane of the cube is a monochromatic reconstruction of the SINFONI FOV.

The north south test template traces each of the 32 slitlets by only one fibre exposure; therefore non linearities of the image scale within the 64 pixel of a single slitlets are currently not corrected and could cause minor slice to slit ripples in the reconstructed cube.

## 9.2 Required input data

To be able to reduce science data one needs to use raw, product data and pipeline recipes in a given sequence which provides all the input necessary to each pipeline recipe. We call this sequence a data reduction cascade. The SINFONI data reduction cascade involves the following input data:

- Reference files:
  - A reference bad pixel map, indicating known detector defects.



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- A list of arc lamp emission lines containing vacuum wavelengths and predicted intensities for wavelength calibration.
- The DRS\_SETUP\_WAVE table as input of `sinfo_rec_distortion` and `sinfo_rec_wavec` to specify parameters peculiar of the wavelength calibration algorithm.
- Raw frames:
  - Linearity flat frames, to determine a map of non linear bad pixels.
  - Darks, to determine master darks.
  - Flat fields, to determine master flats.
  - Fibre frames, to trace the first column of each slitlet and, using also on/off lamp flats and arc lamp frames, to compute the optical distortions and slitlet distances.
  - Arc lamps, to perform the wavelength calibration.
  - Sky frames, to evaluate and subtract the strong and time-variable NIR sky emission.
  - Telluric STD star frames, to correct telluric absorption features.
  - PSF standards, to evaluate the Strehl.
  - Science frames, to finally do science.
- Calibration data products.
  - Bad pixel maps, to correct for the detector defects.
  - Distortion coefficients, to correct for the optical distortions.
  - Master flats, to correct for different detector pixel efficiencies.
  - Master darks, to correct for the instrument bias if no off or sky frames are available.
  - Slitlet distances, to be able to properly reconstruct a cube.
  - Slitlets' left edge positions, to be able to properly reconstruct a cube.
  - Wavelength maps, to obtain a cube calibrated in wavelength.

Calibration data products can be generated from raw data using the pipeline recipes. Alternatively the user may use calibration products obtained from the ESO archive or from the ESO Data Flow Operation department. Master bad pixel maps, the bad pixel maps coming from the standard flats, the master flats, the slitlets position table, the wavelength map depend from the observed band and instrument's pre-optic. Bad pixel maps coming from the non linearity test, distortion tables, slitlet distances, reference line tables depend only on the observed band. The reference bad pixel map, and master darks depend neither from the band nor the pre-optic. Science data requiring master dark need to have matching values of the FITS keyword HIERARCH ESO DET DIT.

### 9.3 Reduction cascade

The SINFONI data reduction follows the following sequence. A short description of the available recipes is given in section 5.1. In parenthesis we provide the value of the DO category corresponding to each frame.

- Run `sinfo_rec_detlin` on a set of flats with increasing intensity (LINEARITY\_LAMP) to determine the non linearity pixels bad pixel map (BP\_MAP\_NL).



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- Run **sinfo\_rec\_mdark** on a set of raw darks (DARK) to determine the master dark (MASTER\_DARK) and the hot pixels bad pixel map (BP\_MAP\_HP). This map depends on DIT.
- Run **sinfo\_rec\_mflat** on a set of standard flat fields (FLAT\_LAMP), the BP\_MAP\_NL and the REF\_BP\_MAP to determine the master bad pixel map (MASTER\_BP\_MAP) and the master lamp flat (MASTER\_FLAT\_LAMP).
- Run **sinfo\_rec\_distortion** on a set of fibre flats (FIBRE\_NS), on/off arc lamps (WAVE\_NS) and on/off lamp flats (FLAT\_NS), using a reference line table (REF\_LINE\_ARC) to determine the optical distortions (DISTORTION) and the slitlet distances (SLITLET\_DISTANCES). To set a few data reduction parameters which depends from the observed band and used instrument pre-optics the user has also to provide in input a DRS\_SETUP\_WAVE table frame.
- Run **sinfo\_rec\_wavecal** on a set of arc lamp frames (FLAT\_WAVE), a MASTER\_BP\_MAP, a MASTER\_FLAT\_LAMP, a DISTORTION, and a REF\_LINE\_ARC to determine the wavelength map (WAVE\_MAP) and the slitlet edge position table (SLIT\_POS). To set a few data reduction parameters which depends from the observed band and used instrument pre-optics the user has also to provide in input a DRS\_SETUP\_WAVE table. If the parameter **wcal-slitpos\_bootstrap** has value set to FALSE, as we suggest for robustness, the user need to provide in input also an appropriate SLIT\_POS table, for example the one we provide as part of data reduction kit.
- Run **sinfo\_rec\_jitter** on PSF standards and a MASTER\_BP\_MAP, a MASTER\_FLAT\_LAMP, a DISTORTION, a SLITLET\_DISTANCES, a SLIT\_POS and a WAVE\_MAP to reduce the PSF standard and get information on the instrument's Strehl.
- Run **sinfo\_rec\_jitter** on a reference telluric standard (STD) and a MASTER\_BP\_MAP, a MASTER\_FLAT\_LAMP, a DISTORTION, a SLITLET\_DISTANCES, a SLIT\_POS and a WAVE\_MAP to reduce the telluric standards and get information on the instrument's response.
- Run **sinfo\_rec\_jitter** on your scientific data (OBJECT\_NODDING) and a MASTER\_BP\_MAP, a MASTER\_FLAT\_LAMP, a DISTORTION, a SLITLET\_DISTANCES, a SLIT\_POS and a WAVE\_MAP to reduce science data.

The main data products involved in the data reduction cascade are indicated in the SINFONI association map shown in Figure 9.3.1. It summarise dependencies between raw data, calibration products and recipes involved in the correction of the instrument signature and reduction of science data. Examples of set of frames input for each recipe are provided in section 10.

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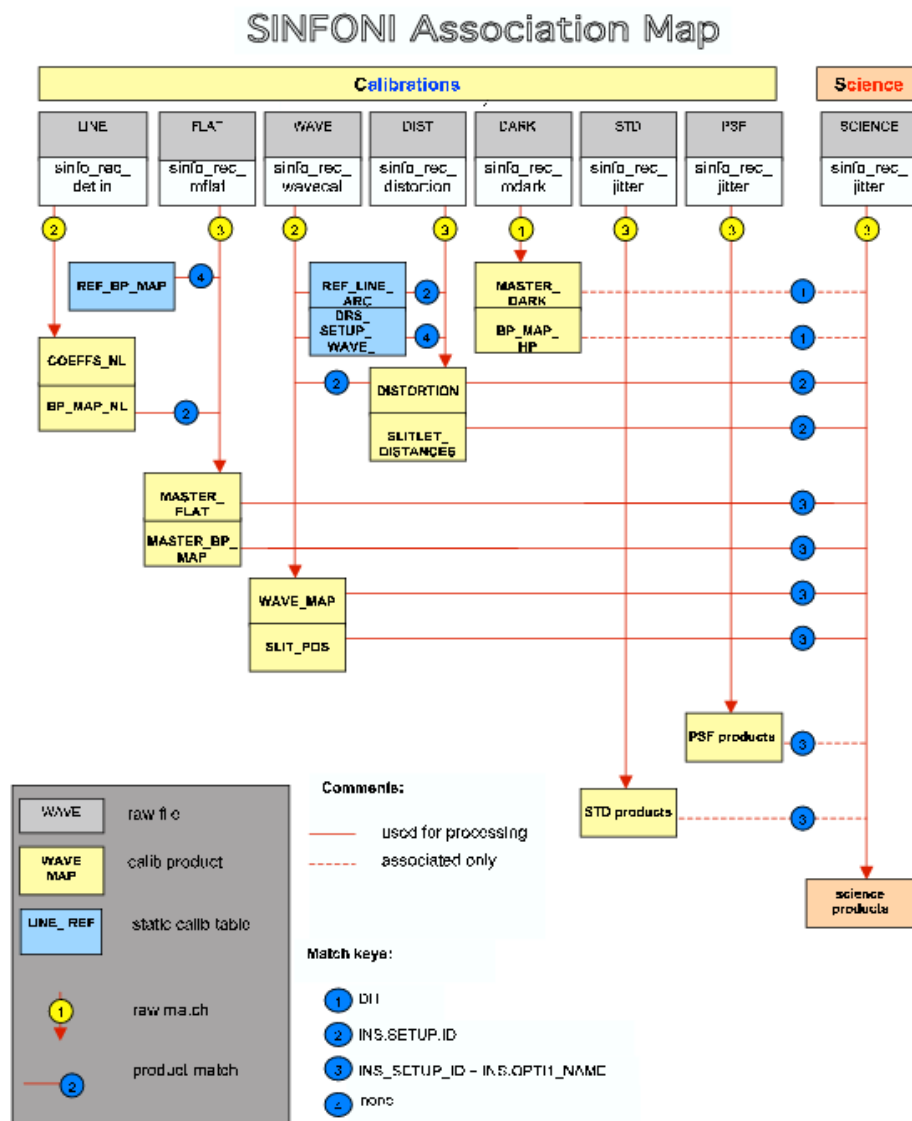


Figure 9.3.1: *SINFONI Association Map*

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## 10 Pipeline Recipes Interfaces

In this section we provide for each recipe examples of the required input data (and their tags). In the following we assume that `/path_file_raw/filename_raw.fits` and `/path_file_cdb/filename_cdb.fits` are existing FITS files (e.g. `/data1/sinfoni/com2/SINFO.2004-08-16T02:54:04.353.fits` and `/cal/sinfo/ifu/cal/DISTORTION_K.fits`).

We also provide a list of the pipeline products for each recipe, indicating their default recipe name (eventually set by `esorex` to a given standard), the value of the FITS keyword `HIERARCH ESO PRO CATG` (in short `PRO.CATG`) and a short description. To improve performance and allow the user to generate different level of information, some recipes may have a variable number of products according to the value of the global parameter **product-density**. If this value is 0 the minimum number of products needed for the data reduction chain is generated. If this value is 1, the recipe **`sinfo_rec_jitter`** generates also some wavelength calibrated cubes needed to be used for eventual sky residual correction. If this value is 2 (default), additional products used for quality control are generated. If this value is 3, all possible products are generated, for debugging purposes. Where relevant we indicate the minimum value of **product-density** which generates the corresponding product in a column labeled as “pd”.

The relevant keywords are `PRO.CATG`, used to classify each frame, and to associate to each raw frame the proper calibration frame:

Association keyword	Information
<code>HIERARCH ESO INS SETUP ID</code>	band
<code>HIERARCH ESO INS OPTI1 NAME</code>	Pixel scale
<code>HIERARCH ESO DET DIT</code>	Integration time
<code>HIERARCH ESO INS1 LAMP5 ST</code>	Indicates the Halogen lamp status (“on”/“off”)

For each recipe we also list in a table the input parameters (as they appear in the recipe configuration file), the corresponding aliases (the corresponding names to be eventually set on command line) and their default values. Also quality control parameters are listed. Those are stored in relevant pipeline products. More information on instrument quality control can be found on [www.eso.org/qc](http://www.eso.org/qc).

We distinguish between recipes involved in the data reduction cascade (having prefix `sinfo_rec`) and user utilities (with prefix `sinfo_util`).

The recipes share the following parameters:

parameter	alias	default
<code>sinfoni.general.override_parameters</code>	<code>gen-overpar</code>	TRUE
<code>sinfoni.general.lc_sw</code>	<code>lc_sw</code>	FALSE
<code>sinfoni.general.lc_kappa</code>	<code>lc_kappa</code>	18
<code>sinfoni.general.lc_filt_rad</code>	<code>lc_filt_rad</code>	3

### 10.1 `sinfo_rec_detlin`

The recipe `sinfo_rec_detlin` computes the detector responsivity as a function of the pixel intensity and determines when it becomes non linear.

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### 10.1.1 Input

```

/path_file_raw/SINFO.2004-08-16T02:54:04.353.fits LINEARITY_LAMP
/path_file_raw/SINFO.2004-08-16T02:53:37.089.fits LINEARITY_LAMP
/path_file_raw/SINFO.2004-08-16T02:52:23.028.fits LINEARITY_LAMP
/path_file_raw/SINFO.2004-08-16T02:51:59.774.fits LINEARITY_LAMP
...
/path_file_raw/SINFO.2004-08-16T02:50:38.991.fits LINEARITY_LAMP
/path_file_raw/SINFO.2004-08-16T02:50:11.797.fits LINEARITY_LAMP
/path_file_raw/SINFO.2004-08-16T02:49:04.887.fits LINEARITY_LAMP
/path_file_raw/SINFO.2004-08-16T02:48:36.792.fits LINEARITY_LAMP

```

### 10.1.2 Output

default recipe file name	PRO.CATG	short description	pd
lin_det_info.fits	LIN_DET_INFO	Table with coefficients of non linear fit to median of each flat image image	2
gain_info.fits	GAIN_INFO	Table with detector's gain values	2
out_bpmlin_coeffsCube.fits	BP_COEFF	cube. Each cube's plane logs coefficients of non linear fit to pixel's intensity used to evaluate non linearity	0
out_bp_lin.fits	BP_MAP_NL	Non linear (bad) pixels map image	0

The LIN\_DET\_INFO table for each on-off linearity flat pair monitors the following values:

- med: median on the whole frame pair difference
- avg: average on the whole frame pair difference
- med\_dit: median divided detector's DIT
- avg\_dit: average divided detector's DIT
- dit: detector's DIT
- adl: values of the product med\_dit\*dit

The GAIN\_INFO table for each on-off linearity flat pair monitor the following values:

- adu: intensity in adu
- gain: corresponding gain

### 10.1.3 Quality control

The pipeline computes the non linear coefficients, the number of non linear pixels per grating, the detector gain.

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**Detector non linearity** The detector non linearity is computed as described in 11.1.9. The computed coefficients are QC.BP-MAP.LINi.MED (i=0,1,2) (see Figure 10.1.1).

A different method is applied to determine the same quantity as described in 11.1.9. The computed coefficients are QC.BP-MAP.LINi.MEAN (i=0,1,2).

**Non linear bad pixels** The pipeline computes the number of non linear bad pixels. Those are given by QC.BP-MAP.NBADPIX and are obtained with the method QC.BP-MAP.METHOD.

**Detector gain** The detector gain is computed as described in 11.1.11 and is given by the value of QC.GAIN. It is expressed in ADU/e<sup>-</sup> units and measures the intensity recorded by the detector for each incident photon. Its inverse is usually called conversion factor.

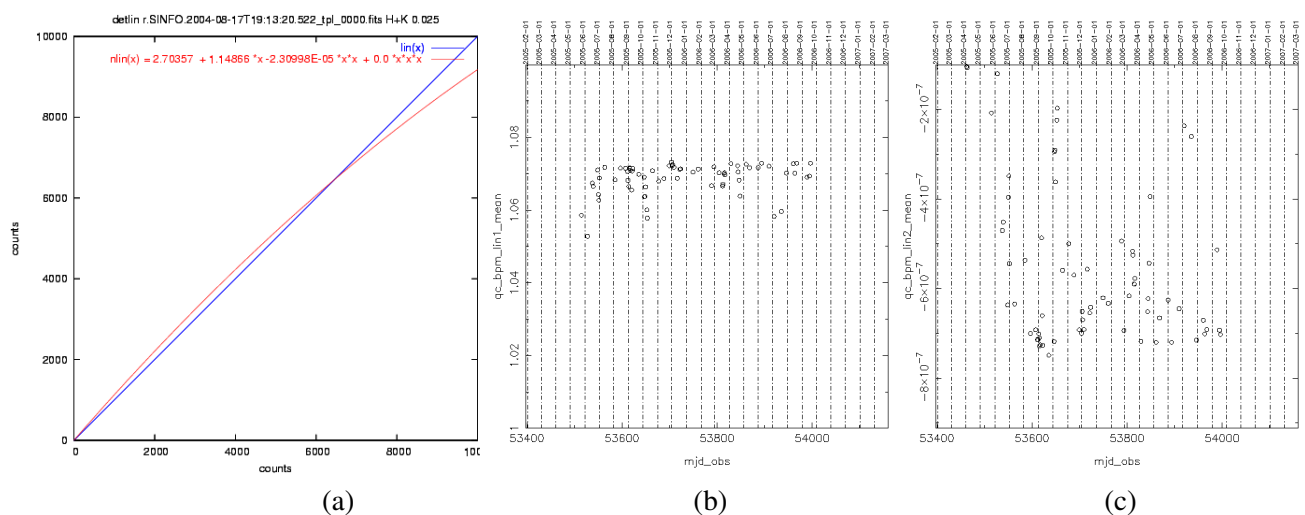


Figure 10.1.1: Detector linearity quality control: (a) the non-linearity function (non-linearity detector response) and a linear relation as a reference; (b) trending plot of detector linearity first order coefficient; (c) trending plot of detector linearity second order coefficient.

## 10.1.4 Parameters

parameter	alias	default
sinfoni.bp_lin.order	bp_lin-order	2
sinfoni.bp_lin.thresh_sigma_factor	bp_lin-thresh_sigma_fct	10.0
sinfoni.bp_lin.nlin_threshold	bp_lin-nlin_threshold	0.5
sinfoni.bp_lin.low_rejection	bp_lin-lo_rej	10.0
sinfoni.bp_lin.high_rejection	bp_lin-hi_rej	10.0

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## 10.2 sinfo\_rec\_lingain

The recipe `sinfo_rec_lingain` reduces linearity and gain of the detector in the infrared domain. The linearity reduction part computes the detector responsivity as a function of the pixel intensity and determines when it becomes non linear. The gain reduction part computes a gain value for each flux level. Both reduction steps are merged in this recipe as both accept the same input interface.

### 10.2.1 Input

This recipe expects a set of pairs of `LINEARITY_LAMP_ON` frames and a set of pairs of `LINEARITY_LAMP_OFF` frames with different exposure time values.

If no modification is done to default behaviour, there must be two frames tagged `LINEARITY_LAMP_ON` and two frames tagged `LINEARITY_LAMP_OFF` for each distinct `EXPTIME` value found among input frames.

The number of distinct `EXPTIME` values among input frames must be at least **order + 1**. This means by default this recipe should receive at least 16 frames.

```
/path_raw/SINFO.2005-09-02T16:44:07.314.fits LINEARITY_LAMP_OFF
/path_raw/SINFO.2005-09-02T16:44:27.248.fits LINEARITY_LAMP_ON
/path_raw/SINFO.2005-09-02T16:44:45.351.fits LINEARITY_LAMP_ON
/path_raw/SINFO.2005-09-02T16:45:57.794.fits LINEARITY_LAMP_OFF
...
/path_raw/SINFO.2005-09-02T17:05:46.234.fits LINEARITY_LAMP_OFF
/path_raw/SINFO.2005-09-02T17:06:37.943.fits LINEARITY_LAMP_ON
/path_raw/SINFO.2005-09-02T17:07:20.400.fits LINEARITY_LAMP_ON
/path_raw/SINFO.2005-09-02T17:08:54.097.fits LINEARITY_LAMP_OFF
```

### 10.2.2 Output

The following table lists all possible products of this recipe. Please note that not all of them are always created. Creation of some of these products depends on the value(s) of some input parameter(s).

If no modification is done to default behaviour, this recipe produces only the first four products in the list.

Further details about conditions for product creation can be found along this section.

For each input setting, the following outputs are created:

Default recipe filename	PRO.CATG	Short description
<code>sinfo_rec_lingain_linearity_table.fits</code>	<code>DET_LIN_INFO</code>	Linearity Table
<code>sinfo_rec_lingain_gain_table.fits</code>	<code>GAIN_INFO</code>	Gain Table
<code>sinfo_rec_lingain_coeffs_cube.fits</code>	<code>COEFFS_CUBE</code>	Coefficients cube
<code>sinfo_rec_lingain_bpm.fits</code>	<code>BP_MAP_NL</code>	Bad pixel map
<code>sinfo_rec_lingain_diff_flat_i.fits</code>	<code>DIFF_FLAT</code>	Difference images
<code>sinfo_rec_lingain_autocorr_i.fits</code>	<code>AUTOCORR</code>	Autocorrelation images

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Both Linearity and Gain Tables are created in all possible execution cases.

### Content of the Linearity Table

For each distinct EXPTIME value, this table logs:

Name	Description
DIT	Detector Integration Time in s
MED	Median intensity of $[(on_1 - off_1) + (on_2 - off_2)]/2$
MEAN	Mean intensity of $[(on_1 - off_1) + (on_2 - off_2)]/2$
MED_DIT	Ratio MED / DIT
MEAN_DIT	Ratio MEAN / DIT
ADL	Column DIT multiplied by mean value of column MED_DIT

### Content of the Gain Table

For each distinct EXPTIME value, this table logs:

Name	Description
DIT	Detector Integration Time in s
MEAN_ON1	Mean intensity of $on_1$ ( $\langle on_1 \rangle$ )
MEAN_ON2	Mean intensity of $on_2$ ( $\langle on_2 \rangle$ )
MEAN_OFF1	Mean intensity of $off_1$ ( $\langle off_1 \rangle$ )
MEAN_OFF2	Mean intensity of $off_2$ ( $\langle off_2 \rangle$ )
SIG_ON_DIF	Standard deviation in $on_1 - on_2$ ( $\sigma_{ondif}$ )
SIG_OFF_DIF	Standard deviation in $off_1 - off_2$ ( $\sigma_{offdif}$ )
GAIN	$\frac{(\langle on_1 \rangle + \langle on_2 \rangle) - (\langle off_1 \rangle + \langle off_2 \rangle)}{(\sigma_{ondif}^2 - \sigma_{offdif}^2)}$
AUTOCORR	Autocorrelation factor
GAIN_CORR	GAIN / AUTOCORR
ADU	$(\langle on_1 \rangle + \langle on_2 \rangle) - (\langle off_1 \rangle + \langle off_2 \rangle)/2$
X_FIT	X-fit coordinate
X_FIT_CORR	X-fit coordinate corrected by the atocorrelation function
Y_FIT	Y-fit coordinate

The Coefficients Cube is created only if **pix2pix** is set to TRUE (default behaviour for this recipe). It contains as many planes as **order** + 1, each pixel in plane **i** indicating the value of the coefficient or order **i** of the fitting computed for that position.

The Bad Pixel map depends on information contained in the Coefficients Cube, so it is created together with it. Its content may vary depending on **bpmbin**.

If **bpmbin** is set to FALSE (default behaviour for this recipe), each pixel has an integer value, power of 2 or combination of powers of 2. Power **i** of 2 means that pixel deviates from the median polynomial coefficient of order **i**.

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If **bpmbin** is set to TRUE, then the Bad Pixel Map will be a binary one, containing only 0 for correct pixels and 1 for all possible bad ones.

The Difference and Autocorrelation images are only created if **intermediate** is set to TRUE (default behaviour for this recipe is FALSE). They represent intermediate steps of the Autocorrelation factor computation.

### 10.2.3 Quality control

**Lamp flux** QC LAMP FLUX in ADU/s.

**Detector gain** The median of the computed gain values and relative stdev QC GAIN MED, QC GAIN STD, in  $e^-/\text{ADU}$  and its inverse QC CONAD in  $\text{ADU}/e^-$ , and the autocorrelation factor QC AUTCORFA.

The median calculated via polynomial fit is also stored as QC GAIN FIT.

**Readnoise** QC READNOISE in  $e^-$ .

And from the linearity part of the recipe:

**Lamp flux RMS** It is monitored the RMS of the lamp flux (QC LAMP STD).

**Non linear coefficients** Are monitored the polynomial fit coefficients (QC LIN COEFi, i=0-2) and the corresponding errors (QC LIN COEFi ERR).

**Effective non linearity** An additional QC parameter is QC LIN EFF, the effective non-linearity correction at a reference user defined level **ref\_level**:  $Q'(\text{ref\_level})$ .

**Number of non polynomial pixels** It is monitored the number of pixels deviating from the polynomial fit (QC NUM BPM).

### 10.2.4 Parameters

Parameter	Alias	Default, Other	Description
sinfo.sinfo_rec_lingain.method	method	<b>PTC, MED</b>	Method applied for Gain Computation
sinfo.sinfo_rec_lingain.order	order	<b>3</b>	Order of the polynomial fitting applied in the Linearity part of the recipe
sinfo.sinfo_rec_lingain.kappa	kappa	<b>9</b>	Multiplier used for Kappa-sigma clipping
sinfo.sinfo_rec_lingain.niter	niter	<b>25</b>	Number of iterations kappa-sigma clipping is applied
sinfo.sinfo_rec_lingain.llx	llx	<b>1</b>	llx of the area to compute
sinfo.sinfo_rec_lingain.lly	lly	<b>1</b>	lly of the area to compute
sinfo.sinfo_rec_lingain.urx	urx	<b>nx of 1. input</b>	urx of the area to compute
sinfo.sinfo_rec_lingain.ury	ury	<b>ny of 1. input</b>	ury of the area to compute



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sinfo.sinfo_rec_lingain.ref_level	ref_level	<b>10000</b>	Reference level on wich linearity efficiency is computed
sinfo.sinfo_rec_lingain.intermediate	intermediate	<b>FALSE, TRUE</b>	Activates saving of intermediate products
sinfo.sinfo_rec_lingain.autocorr	autocorr	<b>FALSE, TRUE</b>	Activates use of Autocorrelation Factor
sinfo.sinfo_rec_lingain.m	m	<b>26</b>	Shift in the X-axis for Autocorrelation
sinfo.sinfo_rec_lingain.n	n	<b>26</b>	Shift in the Y-axis for Autocorrelation
sinfo.sinfo_rec_lingain.collapse	collapse	<b>FALSE, TRUE</b>	Activates collapsing of OFF frames
sinfo.sinfo_rec_lingain.rescale	rescale	<b>TRUE, FALSE</b>	Activates rescaling of images
sinfo.sinfo_rec_lingain.pix2pix	pix2pix	<b>TRUE, FALSE</b>	Activates pixel-to-pixel linearity computation
sinfo.sinfo_rec_lingain.bpmbin	bpmbin	<b>FALSE, TRUE</b>	Activates binary bad pixel map
sinfo.sinfo_rec_lingain.filter	filter	<b>-1</b>	Level beyond which frames are considered saturated and excluded.
sinfo.sinfo_rec_lingain.exts	exts	<b>0</b>	Extension on which recipe is computed

## NOTES

Please note that if ref\_level is not in the interval where Flux(DIT) is monotonely growing (that is, if it is a saturation value) the recipe will fail.

Please note that to compute on all extensions the user must set it to -1 (default is 0 - no extension case).

## 10.3 sinfo\_rec\_mdark

The recipe sinfo\_rec\_mdark generates a master dark from a set of raw darks by stacking frames with rejection of outliers. It also generates a bad pixel map flagging the hot-current pixels.

### 10.3.1 Input

```
/path_file_raw/SINFO.2004-08-16T01:24:53.070.fits DARK
/path_file_raw/SINFO.2004-08-16T01:09:22.905.fits DARK
/path_file_raw/SINFO.2004-08-16T00:53:51.890.fits DARK
/path_file_raw/SINFO.2004-08-16T00:38:14.994.fits DARK
```

### 10.3.2 Output

default recipe file name	PRO.CATG	short description
out_bp_noise.fits	BP_MAP_HP	bad pixel map image, method="Noise"
out_dark.fits	MASTER_DARK	master dark image

### 10.3.3 Quality control

Dark frames are processed to monitor the RON, Read Out Noise per DIT, the FPN, Fixed Pattern Noise per DIT, the detector counts per DIT, the number of hot pixels per DIT.

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**RON** The RON is computed on the whole detector chip and given as value of the QC.RON parameter. For quality control those values are monitored as a function of time and DIT. Two consecutive frames are subtracted from each other and the median standard deviation of a limited number of samples is taken and normalised to DET.NDIT=1. The RON is computed in two regions and is given by the values of QC.RON1 and QC.RON2.

**Dark median counts** The median and standard deviation of the counts in the master dark frame are monitored by DPD. Its value and standard deviation are given by the values of QC.DARKMED.AVE and QC.DARKMED.STDEV

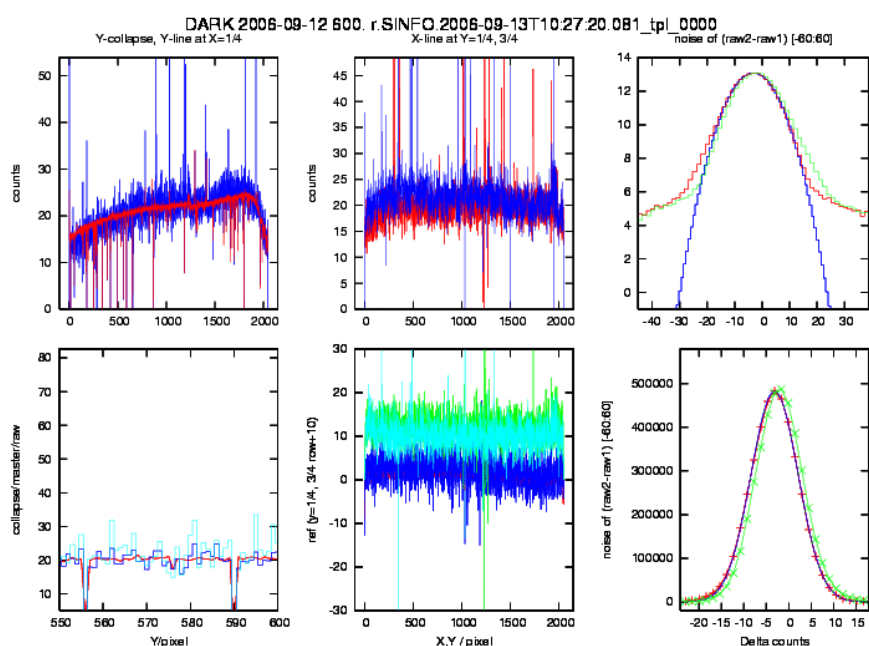


Figure 10.3.1: Dark frame quality control plot: **Upper left:** the mean (collapsed) column (red) and the column at  $X=2048/4$  of the product frame. **Upper middle:** two rows at  $Y=2048/4$  (red) and  $Y=2048*(3/4)$  (blue) of the product frame. **Upper right:** a parabolic function (blue) is fit to the central part (-3 to 3 counts) of the log of the raw2-raw1 difference frame (red). Histogram of the raw3-raw2 difference frame (green). **Lower left:** mean column (collapse), column  $x=500$  of the product and of the first of the three raw input files. A smaller y-range is shown to show the difference between fixed-pattern (=pixel-to-pixel) noise and the statistical noise. **Lower middle:** the  $Y=500$  row of the product minus the  $Y=500$  row of a reference product.  $Y=600$  row of the product minus the  $Y=600$  row of a reference product.  $X=500$  column of the master minus the  $X=500$  column of a reference product. The reference product is renewed usually once a period or after an intervention. **Lower right:** histogram of the difference frame (second row minus first row) (red) and Gaussian fit between -3 and 3 counts (blue). Histogram of the raw3-raw2 difference frame (green).

**Fixed Pattern Noise** The CPL function `cpl_flux_get_noise_window()` is used to compute the FPN. This function computes the noise in a frame with MonteCarlo approach. This value, logged by parameter QC.DARKFPN,

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is monitored for different DITs. The FPN should scale linearly with the number of counts. For this reason the ratio FPN/counts is monitored for different DITs.

**Number of hot pixels** The number of pixels having an intensity greater than a threshold is monitored in the parameter QC.BP-MAP.NBADPIX

### 10.3.4 Parameters

parameter	alias	default
sinfoni.bp_noise.thresh_sigma_factor	bp_noise-thresh_sigma_fct	10.0
sinfoni.bp_noise.low_rejection	bp_noise-lo_rej	10.0
sinfoni.bp_noise.high_rejection	bp_noise-hi_rej	10.0
sinfoni.dark.low_rejection	dark-lo_rej	0.1
sinfoni.dark.high_rejection	dark-hi_rej	0.1
sinfoni.dark.qc_ron_xmin	dark-qc_ron_xmin	1
sinfoni.dark.qc_ron_xmax	dark-qc_ron_xmax	2048
sinfoni.dark.qc_ron_ymin	dark-qc_ron_ymin	1
sinfoni.dark.qc_ron_ymax	dark-qc_ron_ymax	2048
sinfoni.dark.qc_ron_hsize	dark-qc_ron_hsize	4
sinfoni.dark.qc_ron_nsamp	dark-qc_ron_nsamp	100
sinfoni.dark.qc_fpn_xmin	dark-qc_fpn_xmin	1
sinfoni.dark.qc_fpn_xmax	dark-qc_fpn_xmax	2047
sinfoni.dark.qc_fpn_ymin	dark-qc_fpn_ymin	1
sinfoni.dark.qc_fpn_ymax	dark-qc_fpn_ymax	2047
sinfoni.dark.qc_fpn_hsize	dark-qc_ron_hsize	2
sinfoni.dark.qc_fpn_nsamp	dark-qc_ron_nsamp	1000

## 10.4 sinfo\_mdark\_detmon

The recipe detmon\_dark computes the master dark, the Read Out Noise (RON), the Detector Signal Non Uniformity (DSNU).

The input files (at least one) must be tagged as DARK. Files with different DIT are processed separately.

### 10.4.1 Input

```
/path_file_raw/SINFO.2004-08-16T01:24:53.070.fits DARK
/path_file_raw/SINFO.2004-08-16T01:09:22.905.fits DARK
/path_file_raw/SINFO.2004-08-16T00:53:51.890.fits DARK
/path_file_raw/SINFO.2004-08-16T00:38:14.994.fits DARK
```

Here RAW is an alias to be replaced by the instrument specific tag designed to reduce the corresponding data.

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### 10.4.2 Output

default recipe file name	PRO.CATG	short description
sinfo_rec_mdark_detmon_master_dark.fits	MASTER_DARK	master dark frame
sinfo_rec_mdark_detmon_dsnu_map.fits	DSNU_MAP	DSNU image map
sinfo_rec_mdark_detmon_dsnu_table.fits	DSNU_TABLE	DSNU table

### 10.4.3 Quality control

QC DARK, the dark level in ADU.

QC DARK STDEV, the dark level standard deviation in ADU.

### 10.4.4 Parameters

parameter	alias	default
sinfo.sinfo_rec_mdark_detmon.dark.ron.method	ron.method	SIMPLE
sinfo.sinfo_rec_mdark_detmon.dark.dsnu.method	dsnu.method	STDEV
sinfo.sinfo_rec_mdark_detmon.dark.opt_nir	opt_nir	FALSE
sinfo.sinfo_rec_mdark_detmon.dark.exts	exts	0

## 10.5 sinfo\_rec\_mflat

The recipe sinfo\_rec\_mflat computes a master flat field frame and a bad pixel map indicating pixels whose intensity is beyond a given threshold.

### 10.5.1 Input

```

/path_file_raw/SINFO.2005-02-28T16:27:43.232.fits FLAT_LAMP
/path_file_raw/SINFO.2005-02-28T16:28:05.846.fits FLAT_LAMP
/path_file_raw/SINFO.2005-02-28T16:28:18.820.fits FLAT_LAMP
/path_file_raw/SINFO.2005-02-28T16:28:32.593.fits FLAT_LAMP
/path_file_cdb/REF_BP_MAP.fits REF_BP_MAP
/path_file_cdb/BP_MAP_NL_H_025.fits BP_MAP_NL
/path_file_cdb/BP_MAP_HP_H.fits BP_MAP_HP *
/path_file_cdb/BP_MAP_H_025.fits BP_MAP **
/path_file_cdb/SLIT_POS_H_025.fits SLIT_POS **

```

With \* we have indicated a bad pixel map obtained with a list of dark frames. We suggest the user to use darks taken with a low DIT. With \*\* we have listed an additional frames which are required only if **sinfo.lamp\_flats.interpol\_index==TRUE** (usually not the case).

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### 10.5.2 Output

default recipe file name	PRO.CATG	short description	pd
out_flat.fits	MASTER_FLAT_LAMP	master flat field image	0
out_bp_norm.fits	BP_MAP_NO	“Above threshold” bad pixel map image	2
out_bpmap_sum.fits	MASTER_BP_MAP	master bad pixel map image	0

The MASTER\_BP\_MAP results from the logic OR coaddition of the BP\_MAP\_NO image and any other bad pixel map.

### 10.5.3 Quality control

With this recipe one can monitor the lamp efficiency for each grating, the number of bad pixels for each grating, the number of counts in the lamp-off frames, the fixed patten noise in two given regions.

**Lamp flux** The flux of the halogen lamp as measured by the detector depends on the intrinsic brightness of the lamp but also on the spectroscopic setting and the alignment of optical elements. The lamp-off frame is subtracted from the lamp-on frame. The fluxes on this difference frame as computed by the recipe are monitored from the parameter QC.SPECFLAT.NCNTSAVG (the standard deviation of those values is given by QC.SPECFLAT.NCNTSSTD). Day-time spectral flats calibrations come in five pairs of lamp-on and lamp-off frames. Night time calibrations (attached calibrations) come as one pair.

For each lamp-on frame the corresponding lamp-off frame is subtracted and the median is calculated. The QC parameter QC.SPECFLAC.OFFFLUX is the average of these 5 values.

**Bad pixels** The number of bad pixels found on the master lamp flat are monitored from the value of QC.BP-MAP.NBADPIX. The number of bad pixel in the master bad pixel map is given by the value of QC.MBP-MAP.NBADPIX

**Lamp-off flux** It is important to monitor the light/heat contamination in the optical path. The flux measured in lamp-off frames is usually a few counts above the reset anomaly at the same DIT (the dark counts), since a broad band filter is used for the lamp-off frames, while the dark frames are taken with two excluding narrow band filters. The pipeline monitors HIERARCH ESO QC SPECFLAT OFFFLUX, that is the average of the (five) off-lamp medians.

**Fixed Pattern Noise** The pipeline computes the Fixed Pattern noise, in a selected region on the array. This is a simple standard deviation of the flat product frame. The region is specified in the sinfo\_rec\_mflat.rc file. Two regions are monitored by parameters QC.LFLAT.FPN1 and QC.LFLAT.FPN2. During the observing period P75 the first region was the central quarter [@512,@512:@1536,@1536]. In the same observing period the second region was an area on one single slitlet [@1350,@1000:@1390,@1200].

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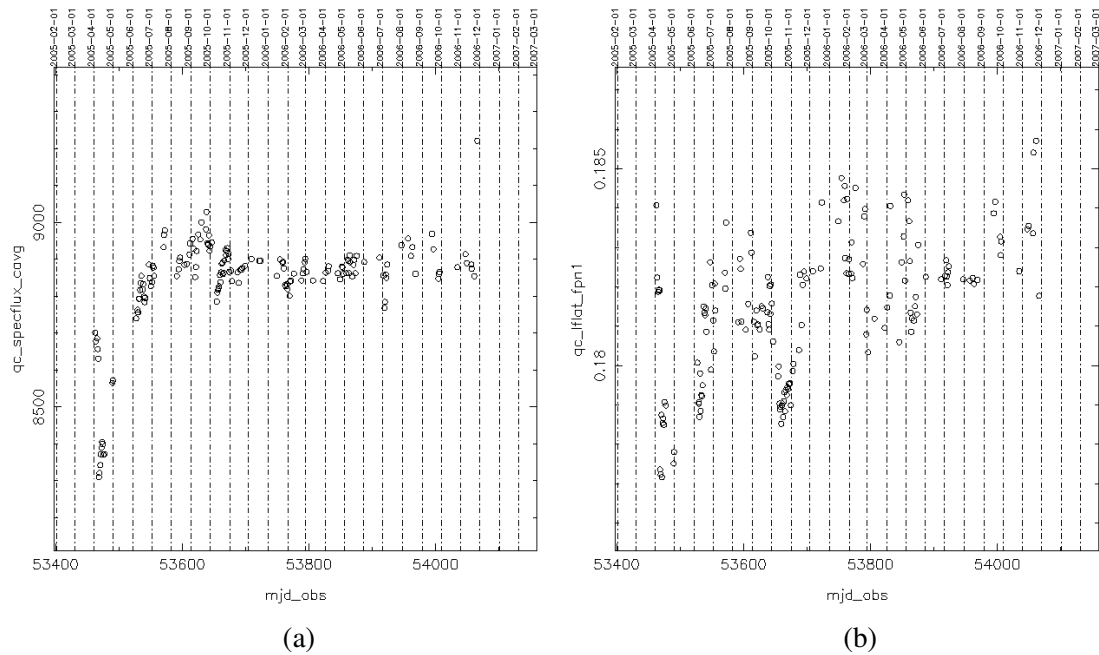


Figure 10.5.1: Detector flat field quality control: (a) Trending plot of lamp average flux; (b) Trending plot of lamp fixed pattern noise in the first reference region.

## 10.5.4 Parameters

parameter	alias	default
sinfoni.bp_norm.sigma_factor	bp_norm-s_factor	5.0
sinfoni.bp_norm.method_index	bp_norm-method_ind	1
sinfoni.bp_norm.factor	bp_norm-fct	10.0
sinfoni.bp_norm.iterations	bp_norm-it	8
sinfoni.bp_norm.low_rejection	bp_norm-lo_rej	0.1
sinfoni.bp_norm.high_rejection	bp_norm-hi_rej	0.1
sinfoni.bp_norm.llx	bp_norm-llx	270
sinfoni.bp_norm.lly	bp_norm-lly	1000
sinfoni.bp_norm.urx	bp_norm-urx	310
sinfoni.bp_norm.ury	bp_norm-ury	1200
sinfoni.bp_norm.threshold_index	bp_norm-thr_ind	TRUE
sinfoni.bp_norm.mean_factor	bp_norm-mean_fct	100.0
sinfoni.bp_norm.min_cut	bp_norm-min_cut	0.0
sinfoni.bp_norm.max_cut	bp_norm-max_cut	5e+04
sinfoni.lamp_flats.low_rejection	lamp_flats-lo_rej	0.1
sinfoni.lamp_flats.high_rejection	lamp_flats-hi_rej	0.1
sinfoni.lamp_flats.interpol_index	lamp_flats-interpol_index	FALSE
sinfoni.lamp_flats.max_rad	lamp_flats-max_rad	4
sinfoni.lamp_flats.bad_ind	lamp_flats-bad_ind	FALSE

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sinfoni.lamp_flats.sigma_factor	lamp_flats-sigma_factor	5.0
sinfoni.lamp_flats.factor	lamp_flats-factor	3.0
sinfoni.lamp_flats.iterations	lamp_flats-iterations	8
sinfoni.lamp_flats.bad_low_rejection	lamp_flats-bad_lo_rej	10.0
sinfoni.lamp_flats.bad_high_rejection	lamp_flats-bad_hi_rej	10.0
sinfoni.lamp_flats.llx	lamp_flats-llx	1350
sinfoni.lamp_flats.lly	lamp_flats-lly	1000
sinfoni.lamp_flats.urx	lamp_flats-rrx	1390
sinfoni.lamp_flats.ury	lamp_flats-ury	1200
sinfoni.lamp_flats.thresh_ind	lamp_flats-tresh_ind	FALSE
sinfoni.lamp_flats.mean_factor	lamp_flats-mean_factor	10.0
sinfoni.lamp_flats.qc_fpn_xmin1	lamp_flats-qc_fpn_xmin1	512
sinfoni.lamp_flats.qc_fpn_xmax1	lamp_flats-qc_fpn_xmax1	1536
sinfoni.lamp_flats.qc_fpn_ymin1	lamp_flats-qc_fpn_ymin1	512
sinfoni.lamp_flats.qc_fpn_ymax1	lamp_flats-qc_fpn_ymax1	1536
sinfoni.lamp_flats.qc_fpn_xmin2	lamp_flats-qc_fpn_xmin2	1350
sinfoni.lamp_flats.qc_fpn_xmax2	lamp_flats-qc_fpn_xmax2	1390
sinfoni.lamp_flats.qc_fpn_ymin2	lamp_flats-qc_fpn_ymin2	1000
sinfoni.lamp_flats.qc_fpn_ymax2	lamp_flats-qc_fpn_ymax2	1200
sinfoni.lamp_flats.qc_thresh_min	lamp_flats-qc_thresh_min	0
sinfoni.lamp_flats.qc_thresh_max	lamp_flats-qc_thresh_max	49000

## 10.6 sinfo\_rec\_distortion

The recipe `sinfo_rec_distortion` is used to compute the optical distortion. It also computes the relative distances of the slitlets from the first one.

### 10.6.1 Input

```

/path_file_raw/SINFO.2004-08-16T13:17:28.050.fits FIBRE_NS
/path_file_raw/SINFO.2004-08-16T13:16:56.095.fits FIBRE_NS
/path_file_raw/SINFO.2004-08-16T13:16:34.352.fits FIBRE_NS
/path_file_raw/SINFO.2004-08-16T13:16:14.839.fits FIBRE_NS
.....
/path_file_raw/SINFO.2004-08-16T13:15:55.156.fits FIBRE_NS
/path_file_raw/SINFO.2004-08-16T13:16:55.156.fits WAVE_NS
/path_file_raw/SINFO.2004-08-16T13:17:55.156.fits WAVE_NS
/path_file_raw/SINFO.2004-08-16T13:18:55.156.fits FLAT_NS
/path_file_raw/SINFO.2004-08-16T13:19:55.156.fits FLAT_NS

/path_file_cdb/neonK.fits REF_LINE_ARC
/path_file_cdb/drs_setup_wave.fits DRS_SETUP_WAVE
/path_file_cdb/BP_MAP_H_025.fits BP_MAP **
/path_file_cdb/SLIT_POS_H_025.fits SLIT_POS **

```

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With \*\* we have listed an additional frames which are required only if `sinfoni.lamp_flats.interpol_index==TRUE` (usually not the case).

To successfully run the distortion recipe are needed: several (usually 75) FIBRE\_NS frames, needed to cover all slitlets and generate an uniformly illuminated synthetic fibre flat; two FLAT\_NS frames, one with calibration flat lamp switched on, one with the lamp switched off; two WAVE\_LAMP frames, one with calibration flat lamp switched on, one with the lamp switched off; and the two static frames, the reference line list of the appropriate band, with tag REF\_LINE\_ARC, and the static parameters table with tag DRS\_SETUP\_WAVE as indicated above.

## 10.6.2 Output

default recipe file name	PRO.CATG	short description	pd
out_flat.fits	MASTER_FLAT_LAMP	master flat field image	2
out_bp_dist.fits	BP_MAP_DI	“Above threshold” bad pixel map image	2
out_ns_stack_off.fits	FIBRE_NS_STACKED_OFF	fake off image from FIBRE,NS	2
out_ns_stack_on.fits	FIBRE_NS_STACKED_ON	fake on image from FIBRE,NS	2
out_ns_stack.fits	FIBRE_NS_STACKED	fake on-off image	2
out_wcal_stack.fits	WAVE_LAMP_STACKED	stacked arc image	2
out_slitlets_pos_predist.fits	SLITLETS_POS_PREDIST	table with computed slitlets edge positions before distortion correction	2
out_distortion.fits	DISTORTION	table computed optical distortions	0
out_ns_stack_warp.fits	FIBRE_NS_STACKED_DIST	on-off image corrected for distortions	2
out_ns.fits	MASTER_SLIT	on-off image multiplied by BP map	2
out_distances.fits	SLITLETS_DISTANCE	table with computed slitlet distances	0

The SLITLETS\_POS\_PREDIST table for each slitlet measure the following values:

- degx: x degree
- degy: y degree
- coeff: polynomial distortion coefficient

The DISTORTION table stores the computed distortion coefficients:

- pos1: left slitlet edge x position
- pos2: right slitlet edge x position

The SLITLET\_DISTANCE table stores the computed slitlets distances from the left edge of the first slitlet:

- slitlet\_distance: computed slitlets distances from the left edge of the first slitlet



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### 10.6.3 Quality control

The recipe `sinfo_rec_distortion` generates the `DISTORTION` product, that is a FITS table containing the coefficients of the optical distortion polynomial. Polynomial coefficients are monitored by `QC.COEFFij`,  $ij=00, 10, 01, 11, 20, 02, 21, 12$ .

Since the coefficients may be difficult to monitor, the optical distortion is applied to five points on the chip. These are the four quadrant centers and the center of the array: (512, 512), (512,1536), (1536,512), (1536,1536) and (1024,1024). The plot shows the location of the five points on the array (like the five symbol on a dice) and the applied shifts in x (along a row), enhanced by a given factor. The optical distortion will shift and shrink the initial dice figure. The QC parameters defined to monitor those shifts are `QC.XSHIFT.CC`, `QC.XSHIFT.LL`, `QC.XSHIFT.LR`, `QC.XSHIFT.UR`, `QC.XSHIFT.UL`.

The second product of the north south test recipe is the `SLITLETS_DISTANCES` product, the relative distance between the 32 slitlets, monitored by `QC.SL.DISTi`,  $i=0,30$ .

Trending describes the variation of a QC1 parameter with time. The following QC1 parameters are determined and monitored:

The recipe `sinfo_rec_distortion` determines the distortion in terms of polynomial coefficients

$$C0 + C1 X + C2 Y + C3 XY + C4 XX + C5 YY + C6 XXY + C7 XYY$$

The recipe also determines the relative pixel distance between consecutive slitlets, a value around 64.

**Distortion coefficients** : The coefficients C0 to C7 are monitored

**Reference pixels shift** : Distortion coefficients are applied to five points on the chip.

**Slitlets Distances** : the average distance between slitlets is monitored together with its uncertainty by QC parameters `QC.SL.DISTAVG`, `QC.SL.DISTRMS`.

### 10.6.4 Parameters

parameter	alias	default
<code>sinfoni.lamp_flats.low_rejection</code>	<code>lamp_flats-lo_rej</code>	0.1
<code>sinfoni.lamp_flats.high_rejection</code>	<code>lamp_flats-hi_rej</code>	0.1
<code>sinfoni.lamp_flats.interpol_index</code>	<code>lamp_flats-interpol_index</code>	FALSE
<code>sinfoni.lamp_flats.max_rad</code>	<code>lamp_flats-max_rad</code>	4
<code>sinfoni.lamp_flats.bad_ind</code>	<code>lamp_flats-bad_ind</code>	FALSE
<code>sinfoni.lamp_flats.sigma_factor</code>	<code>lamp_flats-sigma_factor</code>	5.0
<code>sinfoni.lamp_flats.factor</code>	<code>lamp_flats-factor</code>	3.0
<code>sinfoni.lamp_flats.iterations</code>	<code>lamp_flats-iterations</code>	8
<code>sinfoni.lamp_flats.bad_low_rejection</code>	<code>lamp_flats-bad_lo_rej</code>	10.0
<code>sinfoni.lamp_flats.bad_high_rejection</code>	<code>lamp_flats-bad_hi_rej</code>	10.0

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sinfoni.lamp_flats.llx	lamp_flats-llx	1350
sinfoni.lamp_flats.lly	lamp_flats-lly	1000
sinfoni.lamp_flats.urx	lamp_flats-rrx	1390
sinfoni.lamp_flats.ury	lamp_flats-ury	1200
sinfoni.lamp_flats.thresh_ind	lamp_flats-tresh_ind	FALSE
sinfoni.lamp_flats.mean_factor	lamp_flats-mean_factor	10.0
sinfoni.lamp_flats.qc_fpn_xmin1	lamp_flats-qc_fpn_xmin1	512
sinfoni.lamp_flats.qc_fpn_xmax1	lamp_flats-qc_fpn_xmax1	1536
sinfoni.lamp_flats.qc_fpn_ymin1	lamp_flats-qc_fpn_ymin1	512
sinfoni.lamp_flats.qc_fpn_ymax1	lamp_flats-qc_fpn_ymax1	1536
sinfoni.lamp_flats.qc_fpn_xmin2	lamp_flats-qc_fpn_xmin2	1350
sinfoni.lamp_flats.qc_fpn_xmax2	lamp_flats-qc_fpn_xmax2	1390
sinfoni.lamp_flats.qc_fpn_ymin2	lamp_flats-qc_fpn_ymin2	1000
sinfoni.lamp_flats.qc_fpn_ymax2	lamp_flats-qc_fpn_ymax2	1200
sinfoni.lamp_flats.qc_thresh_min	lamp_flats-qc_thresh_min	0
sinfoni.lamp_flats.qc_thresh_max	lamp_flats-qc_thresh_max	49000
sinfoni.bp.method	bp-method	Normal
sinfoni.bp_dist.sigma_factor	bp_dist-s_factor	2.0
sinfoni.bp_dist.method_index	bp_dist-method_ind	1
sinfoni.bp_dist.factor	bp_dist-fct	999.0
sinfoni.bp_dist.iterations	bp_dist-it	8
sinfoni.bp_dist.low_rejection	bp_dist-lo_rej	0.1
sinfoni.bp_dist.high_rejection	bp_dist-hi_rej	0.1
sinfoni.bp_dist.llx	bp_dist-llx	1350
sinfoni.bp_dist.lly	bp_dist-lly	1000
sinfoni.bp_dist.urx	bp_dist-urx	1390
sinfoni.bp_dist.ury	bp_dist-ury	1200
sinfoni.bp_dist.threshold_index	bp_dist-thr_ind	TRUE
sinfoni.bp_dist.mean_factor	bp_dist-mean_fct	999.0
sinfoni.bp_dist.min_cut	bp_dist-min_cut	0.0
sinfoni.bp_dist.max_cut	bp_dist-max_cut	5e+04
sinfoni.stack.low_rejection	stack-lo_rej	0.1
sinfoni.stack.high_rejection	stack-hi_rej	0.1
sinfoni.stack.flat_index	stack-flat_ind	TRUE
sinfoni.stack.mask_index	stack-mask_ind	1
sinfoni.stack.ind_index	stack-ind_ind	FALSE
sinfoni.stack.mask_rad	stack-mask_rad	4
sinfoni.stack.gauss_index	stack-gauss_ind	FALSE
sinfoni.stack.kernel_half_width	stack-khw	2
sinfoni.stack.warpx_ind	stack-warpx_ind	TRUE
sinfoni.stack.warpx_kernel	stack-warpx_kernel	tanh
sinfoni.stack.qc_thresh_min	stack-qc_thresh_min	0
sinfoni.stack.qc_thresh_max	stack-qc_thresh_max	64000
sinfoni.distortion.calib_indicator	dist-calib_indicator	TRUE
sinfoni.distortion.min_diff_mean_med_col_int	dist-min_diff_mean_med_col_int	10.0

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sinfoni.distortion.half_width	dist-hw	7
sinfoni.distortion.sigma	dist-sigma	2.0
sinfoni.distortion.fwhm	dist-fwhm	2.0
sinfoni.distortion.min_amplitude	dist-min_amplitude	5.0
sinfoni.distortion.max_residual	dist-max_residual	0.5
sinfoni.distortion.n_a_coefficients	dist-n_a_coeffs	4
sinfoni.distortion.n_b_coefficients	dist-n_b_coeffs	2
sinfoni.distortion.sigma_factor	dist-sigma_factor	1.5
sinfoni.distortion.write_coeffs_ind	dist-wcoeff_ind	TRUE
sinfoni.distortion.write_par_ind	dist-par_ind	TRUE
sinfoni.distortion.pixel_dist	dist-pixel-dist	12
sinfoni.distortion.pixel_tol	dist-pixel_tol	3.0
sinfoni.distortion.wave_map_ind	dist-wave_map_ind	FALSE
sinfoni.distortion.mag_factor	dist-mag_factor	8
sinfoni.distortion.slit_pos_indicator	dist-slit_pos_ind	TRUE
sinfoni.distortion.fit_boltz_indicator	dist-fit_boltz_ind	TRUE
sinfoni.distortion.fit_edge_indicator	dist-fit_edge_ind	FALSE
sinfoni.distortion.estimate_indicator	dist-estimate_ind	FALSE
sinfoni.distortion.box_length	dist-box_len	32
sinfoni.distortion.y_box	dist-y_box	5.0
sinfoni.distortion.diff_tol	dist-diff_toll	2.0
sinfoni.distortion.qc_thresh_min	dist-qc_thresh_min	0
sinfoni.distortion.qc_thresh_max	dist-qc_thresh_max	64000
sinfoni.distortion.lower_rejection	ns-lo_rejection	0.1
sinfoni.distortion.higher_rejection	ns-hi_rejection	0.1
sinfoni.distortion.mask_ind	ns-mask_ind	FALSE
sinfoni.distortion.gauss_ind	ns-gauss_ind	FALSE
sinfoni.distortion.kernel_half_width	ns-khw	2
sinfoni.distortion.ns_half_width	ns-hw	4
sinfoni.distortion.ns_fwhm	ns-fwhm	2.0
sinfoni.distortion.min_diff	ns-min_diff	1.0
sinfoni.distortion.dev_tol	ns-dev_tol	20.0
sinfoni.distortion.arcs_thresh_factor	arcs_thresh_factor	0.33333
sinfoni.distortion.arcs_min_arclen_factor	arcs_min_arclen_factor	1.19
sinfoni.distortion.arcs_window_size	arcs_window_size	14
sinfoni.distortion.smooth_rad	smooth_rad	3
sinfoni.north_south_test.low_rejection	ns-lo_rej	0.1
sinfoni.north_south_test.high_rejection	ns-hi_rej	0.1
sinfoni.north_south_test.mask_ind	ns-mask_ind	FALSE
sinfoni.north_south_test.gauss_ind	ns-gauss_ind	FALSE
sinfoni.north_south_test.kernel_half_width	ns-khw	2
sinfoni.north_south_test.half_width	ns-hw	4
sinfoni.north_south_test.fwhm	ns-fwhm	2.0
sinfoni.north_south_test.min_diff	ns-min_diff	1.0
sinfoni.north_south_test.dev_tol	ns-dev_tol	20.0

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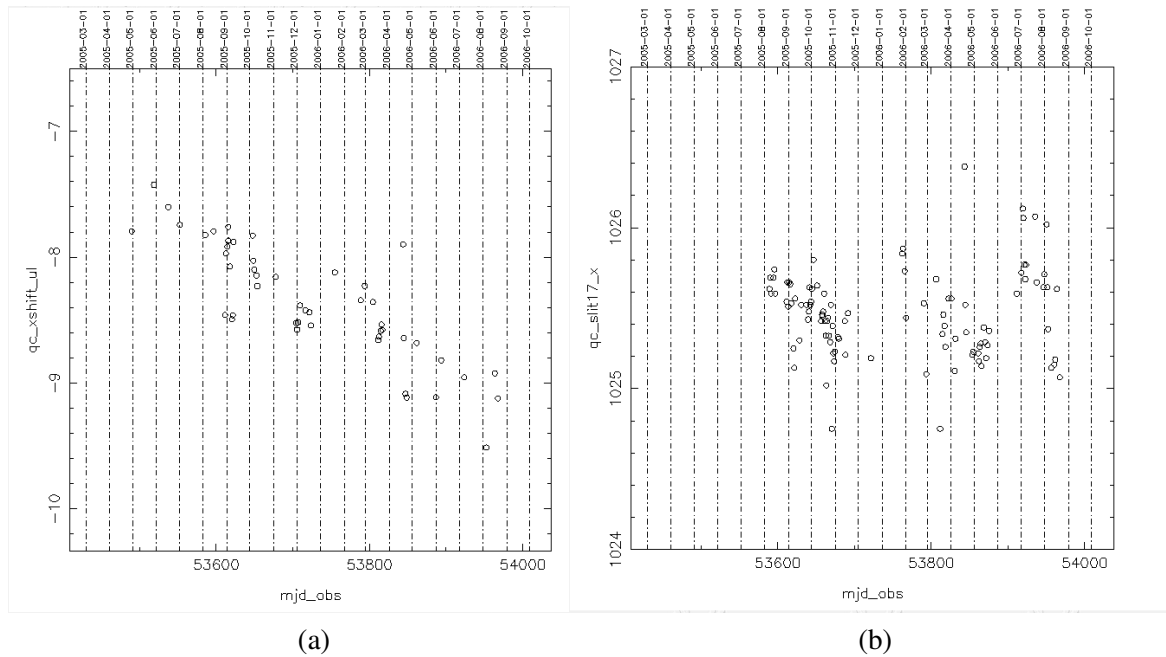


Figure 10.6.1: Optical distortions quality control: (a) trending plot of upper left X shift; (b) trending plot of slitlet # 17 position.

## 10.7 sinfo\_rec\_wavecal

The recipe `sinfo_rec_wavecal` is used to determine the wavelength dispersion coefficients and construct a wavelength calibration map. It also determines the positions of the edges of each slitlet.

### 10.7.1 Input

```
/path_file_raw/SINFO.2004-08-15T11:26:49.348.fits WAVE_LAMP
/path_file_raw/SINFO.2004-08-15T11:26:19.304.fits WAVE_LAMP
/path_file_cdb/neonK.fits REF_LINE_ARC
/path_file_cdb/MASTER_FLAT_LAMP_K_100.fits MASTER_FLAT_LAMP
/path_file_cdb/MASTER_BP_MAP_K_100.fits MASTER_BP_MAP
/path_file_cdb/DISTORTION_K.fits DISTORTION
/path_file_cdb/drs_setup_wave.fits DRS_SETUP_WAVE
/path_file_cdb/SLIT_POS_K_100.fits SLIT_POS
```

The slitlet position table, classified as `SLIT_POS`, is a necessary input if the parameter `wcal-slitpos_bootstrap` is set to `FALSE`, which we suggest for robustness. As this is also a product of this step, we have provided a complete list of master calibrations for this frame as part of the data reduction kit. If the user would like to set the parameter `wcal-estimate_ind` to `TRUE`, an additional input table to have a guess of the slitlet positions must be provided, with the classification `SLIT_POS_GUESS`. The user may for example use for this table a copy of the appropriate (band, pre-optics) provided `SLIT_POS`. If the parameter `wcal-calib_indicator` is set to

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FALSE, the user has to provide also the parabolic fit coefficients table, to be classified as WAVE\_COEF\_SLIT, for example the one which can be obtained running the recipe with **wcal-calib\_indicator** set to TRUE (default).

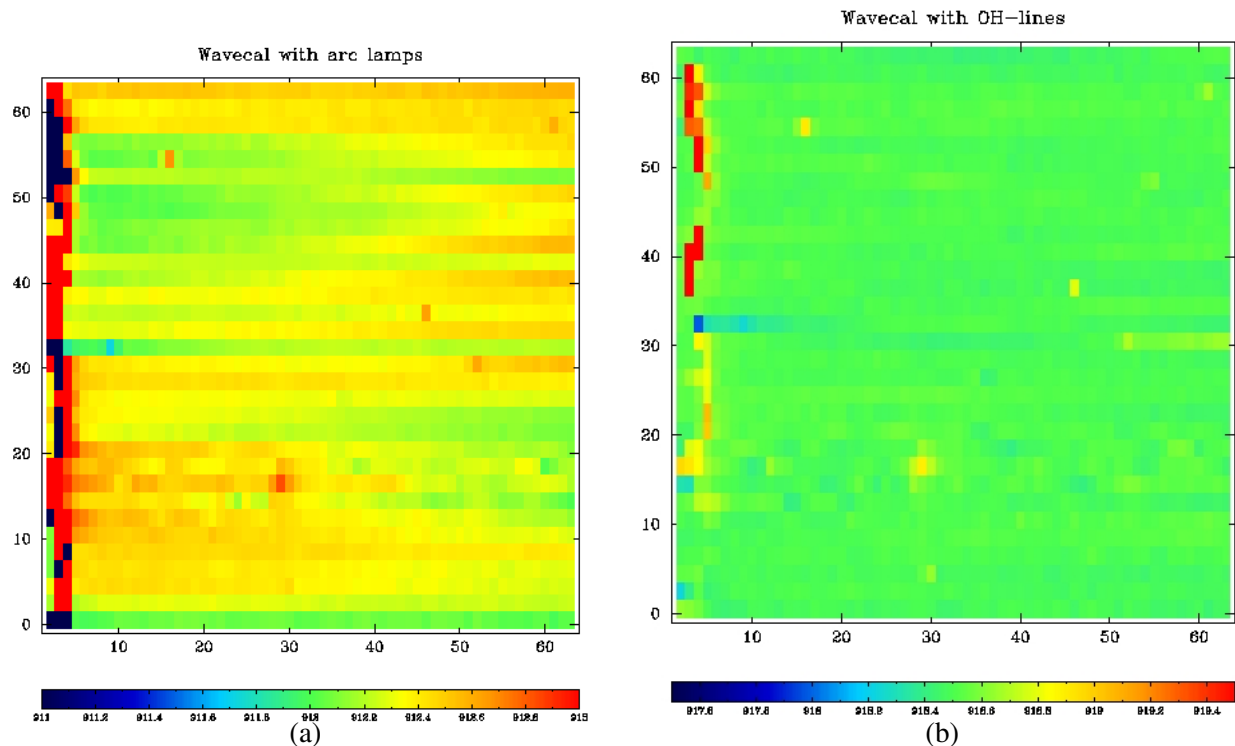


Figure 10.7.1: Wavelength calibration based on arcs and sky lines: (a) Object cube planes calibrated using a wave map generated using arc lamp frames; (b) Object cube planes calibrated using a wave map generated using sky frames; The more uniform color palette of image (b) is an indication of higher accuracy in the SINFONI FOV. Images refers to H band observations.

Since release 1.9.8 the user may also perform an OH based wavelength calibration. In this case in place of the on/off arc lamp frames, one needs to input a sky frame (tagged as SKY\_NODDING) and an dark frame (tagged as MASTER\_DARK). The WAVE\_MAP that one may obtain in this way may grant a better science data reduction accuracy if used in input of the siunfo\_rec\_jitter recipe.

```
/path_file_raw/SINFO.2008-10-01T03:26:49.348.fits SKY_NODDING
/path_file_cdb/MASTER_DARK.fits MASTER_DARK
/path_file_cdb/neonK.fits REF_LINE_ARC
/path_file_cdb/MASTER_FLAT_LAMP_K_100.fits MASTER_FLAT_LAMP
/path_file_cdb/MASTER_BP_MAP_K_100.fits MASTER_BP_MAP
/path_file_cdb/DISTORTION_K.fits DISTORTION
/path_file_cdb/drs_setup_wave_band.fits DRS_SETUP_WAVE
/path_file_cdb/SLIT_POS_K_100.fits SLIT_POS
```

Notes:

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the input table tagged as DRS\_SETUP\_WAVE, has different values of W\_LOW\_POS and W\_HI\_POS for H band, the appropriate ones for a SKY frame in H band, as in the case we have performed tests. We provide this table in the file drs\_setup\_wave\_oh.fits part of the demo distribution. The user willing to use sky lines to perform the wavelength calibration on other bands, need to change the W\_LOW\_POS and W\_HI\_POS values for the column corresponding to the band of interest, so that the specified Y range includes at least one (or a few) sky line(s) with good signal to noise ratio.

For accuracy one needs to have input sky frames with sufficiently high signal to noise ratio. This is usually the case for 250 mas observations, and often in case of 100 mas observations. In case of 25 mas observations the signal to noise ratio is usually too low to use the frame for wavelength calibration, unless one may acquire deep sky exposures (that on the other side are affected by sky lines temporal variations).

While for H and J band an OH based wavelength calibration may work, in K band it may be less robust/accurate beyond 2.3 um, due to absence of OH lines. We leave the decision about using sky frames as input of this recipe to the user.

### 10.7.2 Output

default recipe file name	PRO.CATG	short description	pd
out_stack_mflat_dist.fits	MFLAT_STACKED_DIST	stacked FLAT,LAMP image	2
out_wcal_stack.fits	WAVE_LAMP_STACKED	stacked WAVE,LAMP image	2
out_wavemap_ima.fits	WAVE_MAP	wavelength map image: wavelength=intensity	0
outCoeffsSlit.fits	WAVE_COEF_SLIT	table with parabolic fit coefficients, for each pixel	2
out_fit_params.fits	WAVE_FIT_PARAMS	table with parameters relative to the fit of lines	2
out_slitpos.fits	SLIT_POS	slitlets positions	0
out_resampled_arclamp.fits	RESAMPLED_WAVE	stacked, resampled WAVE,LAMP image	2

The WAVE\_COEF\_SLIT table stores the computed polynomial coefficients:

- coeff0: coefficient polynomial term order 0
- coeff1: coefficient polynomial term order 1
- coeff2: coefficient polynomial term order 2
- coeff3: coefficient polynomial term order 3

The WAVE\_FIT\_PARAMS table stores the computed parameters of lines fit:

- n\_params: number of rows in table
- column: detector's column number
- line: increasing value of line ID
- fpar0: line Gaussian amplitude
- dpar0: line Gaussian amplitude's error

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- fpar1: line FWHM
- dpar1: line FWHM's error
- fpar2: line center
- dpar2: line center's error
- fpar3: line background
- dpar3: line background's error

The SLIT\_POS table stores the computed slitlets left and right edges positions:

- pos1: left slitlet edge position
- pos2: right slitlet edge position

### 10.7.3 Quality control

The recipe monitors the resolving power, the overall wavelength dispersion offset in  $\mu m$  and pixels, the slitlets position in pixels.

**Dispersion solution** The recipe returns several QC parameters. Among them the average and median coefficients of the wavelength solution (QC.COEFi.AVG, QC.COEFi.MED, i=0,3). The measured wavelength can be compared against the encoder value (INS.GRAT1.WLEN) and the nominal values (e.g. 2.2000  $\mu m$  for the S3\_K grating). During commissioning the grating have been set up in a way that the average and central wavelengths coincides with the nominal values.

The resolving power is monitored as the FWHM of the found arc lines (QC.FWHM.MED, QC.FWHM.AVG) divided by the central wavelength.

**Offset** DPD monitors the offset between the central wavelength as returned by the recipe and the grating encoder value (measured value minus encoder value). Assuming that the grating initializes with the same encoder value, this parameter nominally measures the intrinsic errors of the pipeline recipe.

The offset between nominal central wavelength (as given by 1.250 J, 1.650 H, 2.200 K, 1.950 H+K) and the corresponding measured one as given by the wavecal recipe in pixel units (measured minus nominal) are monitored.

The offset between the encoder value and the nominal central wavelength, as given by 1.250 J, 1.650 H, 2.200 K, 1.950 H+K (encoder minus nominal) allows to monitor the position stability/variability of the grating.

**Overall wavelength calibration error** The value of QC.WAVE.POSERR indicates an estimate of the overall positioning error found during the wavelength calibration.

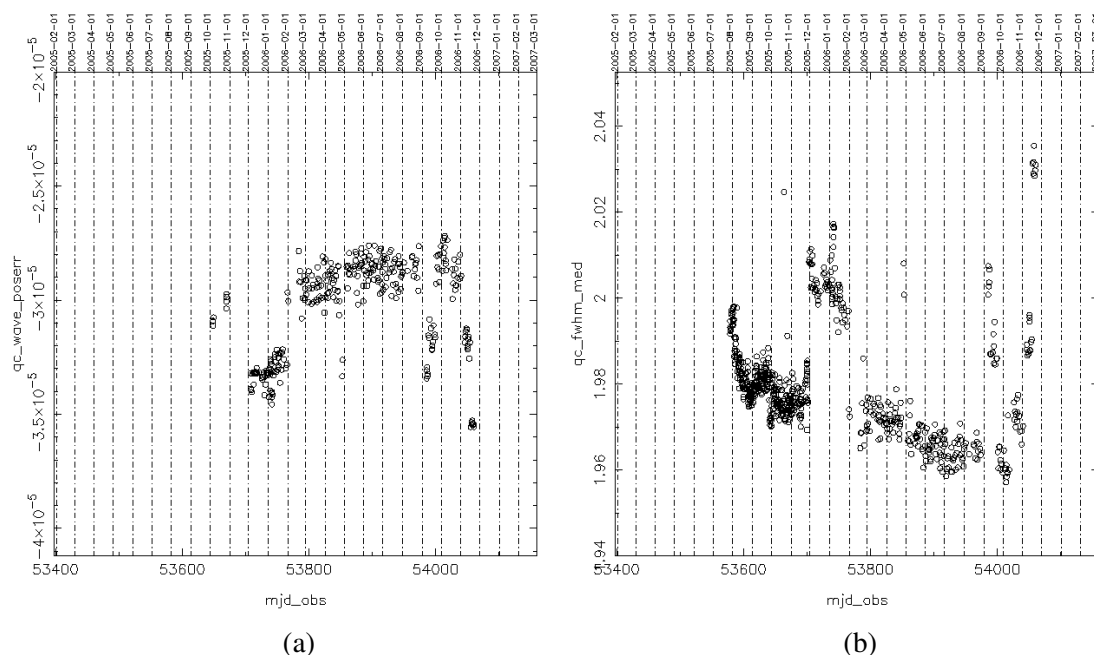


Figure 10.7.2: Wavelength calibration quality control: (a) trending plot of overall positioning error; (b) trending plot of median line's FWHM.

**Maximum flux** The maximum flux in an arc lamp frame, given by the value of QC.FRMON.MAXFLUX, gives an indication of the arc lamp aging.

**Resampled arc lamp frame** This frame is used for quality control to check the wavelength calibration accuracy (after frame resampling).

#### 10.7.4 Parameters

parameter	alias	default
sinfoni.stacked.low_rejection	stack-lo_rej	0.1
sinfoni.stacked.high_rejection	stack-hi_rej	0.1
sinfoni.stacked.flat_index	stack-flat_ind	TRUE
sinfoni.stacked.mask_index	stack-mask_ind	1
sinfoni.stacked.ind_index	stack-ind_ind	FALSE
sinfoni.stacked.mask_rad	stack-mask_rad	4
sinfoni.stacked.gauss_index	stack-gauss_ind	FALSE
sinfoni.stacked.kernel_half_width	stack-khw	2
sinfoni.stacked.warpfix_ind	stack-warpfix_ind	TRUE
sinfoni.stacked.warpfix_kernel	stack-warpfix_kernel	tanh
sinfoni.stack.qc_thresh_min	stack-qc_thresh_min	0
sinfoni.stack.qc_thresh_max	stack-qc_thresh_max	64000



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sinfoni.wavecal.slitpos_bootstrap_switch	wcal-slitpos_bootstrap	FALSE
sinfoni.wavecal.calib_indicator	wcal-calib_indicator	TRUE
sinfoni.wavecal.min_diff	wcal-min_diff	1
sinfoni.wavecal.half_width	wcal-hw	7
sinfoni.wavecal.sigma	wcal-sigma	2.0
sinfoni.wavecal.fwhm	wcal-fwhm	2.83
sinfoni.wavecal.min_amplitude	wcal-min_amplitude	5.0
sinfoni.wavecal.max_residual	wcal-max_residual	0.5
sinfoni.wavecal.n_a_coefficients	wcal-n_a_coeffs	4
sinfoni.wavecal.n_b_coefficients	wcal-n_b_coeffs	2
sinfoni.wavecal.sigma_factor	wcal-sigma_factor	1.5
sinfoni.wavecal.write_coeffs_ind	wcal-wcoeff_ind	TRUE
sinfoni.wavecal.write_par_ind	wcal-par_ind	TRUE
sinfoni.wavecal.pixel_dist	wcal-pixel_dist	12
sinfoni.wavecal.pixel_tol	wcal-pixel_tol	3.0
sinfoni.wavecal.wave_map_ind	wcal-wave_map_ind	FALSE
sinfoni.wavecal.mag_factor	wcal-mag_factor	8
sinfoni.wavecal.slit_pos_indicator	wcal-slit_pos_ind	TRUE
sinfoni.wavecal.fit_boltz_indicator	wcal-fit_boltz_ind	TRUE
sinfoni.wavecal.fit_edge_indicator	wcal-fit_edge_ind	FALSE
sinfoni.wavecal.estimate_indicator	wcal-estimate_ind	FALSE
sinfoni.wavecal.box_length	wcal-box_len	32
sinfoni.wavecal.y_box	wcal-y_box	5.0
sinfoni.wavecal.diff_tol	wcal-diff_toll	2.0
sinfoni.wavecal.qc_thresh_min	wcal-qc_thresh_min	0
sinfoni.wavecal.qc_thresh_max	wcal-qc_thresh_max	64000

## 10.8 sinfo\_rec\_jitter

The recipe `sinfo_rec_jitter` reduces PSF standard, telluric standard or other scientific targets data. It subtracts the sky, corrects for the flat-field and resamples the data by constructing a wavelength calibrated cube in which each plane is a monochromatic image of the FOV. A cube is generated for each target object. Finally a mosaic of all the cubes is reconstructed. Finally it measures the PSF FWHM (x and y) and computes the instrument Strehl and the encircled energy. Moreover for target frames whose point spread function may be approximated by a 2D Gaussian, it extract the object average spectrum and computes the instrument+detector+telescope efficiency.

### 10.8.1 Input

```

/path_file_raw/SINFO.2004-08-13T03:26:12.559.fits PSF_CALIBRATOR
/path_file_raw/SINFO.2004-08-13T03:25:30.323.fits SKY_PSF_CALIBRATOR
/path_file_cdb/MASTER_BP_MAP_K_250.fits MASTER_BP_MAP
/path_file_cdb/MASTER_FLAT_LAMP_K_250.fits MASTER_FLAT_LAMP
/path_file_cdb/WAVE_MAP_K_250.fits WAVE_MAP
/path_file_cdb/SLIT_POS_K_250.fits SLIT_POS

```

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/path\_file\_cdb/SLITLETS\_DISTANCE\_K.fits SLITLETS\_DISTANCE  
 /path\_file\_cdb/DISTORTION\_K.fits DISTORTION  
 /path\_file\_cdb/ATM\_REF\_CORR\_J\_025.fits ATM\_REF\_CORR

The ATM\_REF\_CORR frame is necessary to compute the correction due atmospheric refraction (see Section 11.1.30). The frame is optional. The correction is applied only if this input frame is provided.

## 10.8.2 Output

default recipe file name	PRO.CATG	short description	pd
sky00.fits	SKY_STACKED_DUMMY	stacked sky image	2
out_sky_stack_dist0.fits	SKY_STACKED_DIST	stacked sky image distortion corrected	2
out_stack_mflat_dist.fits	MFLAT_STACKED_DIST	stacked master flat image	2
out_stackN.fits	X_CALIBRATOR_STACKED	stacked X image, N=0,1,...	0
out_resampled_obj0.fits	RESAMPLED_OBJ	stacked, resampled object image	2
out_resampled_sky0.fits	RESAMPLED_SKY	stacked, resampled sky image	2
out_resampled_flat0.fits	RESAMPLED_FLAT_LAMP	stacked, resampled flat image	2
		distortions corrected	
out_sky_cube00.fits	OBS_SKY	sky cube	1
out_sky_med00.fits	SKY_MED	SKY_CUBE z-median image	2
out_mflat_cube.fits	MFLAT_CUBE	Master flat cube	2
out_mflat_avg.fits	MFLAT_AVG	MFLAT_CUBE z-mean image	2
out_mflat_med.fits	MFLAT_MED	MFLAT_CUBE z-median image	2
out_cube_objNN.fits	OBS_X	X cube, NN=00,01,...	0
out_cube_obj_corNN.fits *	OBS_X	X cube, sky residual corrected, NN=00,01,...	1/3
out_int_objNN.fits *	QC_SPECTRA	QC info on sky residual corrected spectra	1/3
out_objnod.fits	COADD_X	coadded cube	0
out_objnod_med_cube.fits	MED_COADD_X	COADD_X z-median image	0
out_objnod_bmap.fits	MASK_COADD_X	COADD_X's mask cube	0
out_ao_performance.fits	AO_PERFORMANCE	table with strehl information	0
out_encircled_energy.fits	ENC_ENERGY	table with encircled energy information	0
out_psf.fits	MASTER_PSF	z-median of COADD_X	0
out_std_star_spectrum.fits	STD_STAR_SPECTRA	table with extracted spectrum, and efficiency information for COADD_X	0
out_starspectrum.fits	STD_STAR_SPECTRUM	collapsed image spectrum COADD_X	0

Here X=PSF or STD or OBJ if in input are PSF or telluric standards or other science frames. Product indicated with \* are produced only if **product-density** is set to 1 or 3 and **objnod-sky\_cor** is set to TRUE.

The last five frames are generated only in case of input PSF or STD frames.

The AO\_PERFORMANCE table stores information about the computed Strehl:

- wavelength: wavelength at which Strehl is computed
- strehl: Strehl value
- strehl\_error: Strehl error

The STD\_STAR\_SPECTRA table stores information about the extracted spectrum:

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- wavelength: wavelength [um]
- counts\_tot: total counts integrated in a given window [ADU]
- counts\_bkg: total counts - background counts in the same window [ADU]
- bkg\_tot: background counts in the same window [ADU]

The ENCIRCLED\_ENERGY table stores information about the encircled energy:

- r\_pix: radii in pix units
- r\_mas: radii in milli arcsecs
- r\_dif: radii in utints of diffraction limit radii
- abs\_energy: absolute encircled energy, the flux integrated in a circle of radius r\_pix centered on the maximum position (star position) of the image obtained by median collapsing the star cube.
- rel\_energy: relative encircled energy, equal to abs\_energy divided by the maximum value of the image obtained by median collapsing the star cube.

### 10.8.3 Quality control

QC.STREHLi log the instrument's Strehl at wavelength QC.LAMBDAi. It also logged the median Strehl (QC.STREHL.MED) and the mean Strehl (QC.STREHL.AVG), and the error associated to the median Strehl (QC.STREHL.MEDERR). The values of QC.PUPILi.SHIFTX, QC.PUPILi.SHIFTY, indicate the position of the centroid of the pupil image. QC.ENC.CORE give the encircled energy in the PSF's core. QC.FWMX, QC.FWHMY, QC.CONVFCT, QC.CHECKi, QC.SHIFTX, QC.SHIFTY. The values of QC.FWHM.LLX and QC.FWHM.LLY indicate the position of the lower left X and Y position of the rectangular box where a 2D Gaussian fit to the object PSF is calculated to extract the object spectrum and the QC.FWHM.HBX and QC.FWHM.HBY are the corresponding half box sizes. The parameters QC.FWHM.MAJ, QC.FWHM.MIN, QC.THETA indicate the size of the major and minor ellipsoid axes and their angle with respect to the X-Y standard axes in the 2D ellipsoid fit to the image PSF. For the quality control are also computed the heliocentric and barycentric radial velocity corrections, QC.VRAD.HELICOR and QC.VRAD.BARYCOR. Those corrections are not applied to the 3D cube.

### 10.8.4 Parameters

parameter	alias	default
sinfoni.product.density	product-density	1
sinfoni.stacked.low_rejection	stack-lo_rej	0.1
sinfoni.stacked.high_rejection	stack-hi_rej	0.1
sinfoni.stacked.flat_index	stack-flat_ind	TRUE
sinfoni.stacked.mask_index	stack-mask_ind	1
sinfoni.stacked.ind_index	stack-ind_ind	FALSE

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sinfoni.stacked.mask_rad	stack-mask_rad	4
sinfoni.stacked.gauss_index	stack-gauss_ind	FALSE
sinfoni.stacked.kernel_half_width	stack-khw	2
sinfoni.stacked.warpfix_ind	stack-warpfix_ind	TRUE
sinfoni.stacked.warpfix_kernel	stack-warpfix_kernel	tanh
sinfoni.stack.qc_thresh_min	stack-qc_thresh_min	0
sinfoni.stack.qc_thresh_max	stack-qc_thresh_max	64000
sinfoni.objnod.autojitter_method	objnod-aj_method	1
sinfoni.objnod.scales_sky	objnod-scales_sky	FALSE
sinfoni.objnod.ks_clip	objnod-ks_clip	TRUE
sinfoni.objnod.kappa	objnod-kappa	2.0
sinfoni.objnod.size_x	objnod-size_x	0
sinfoni.objnod.size_y	objnod-size_y	0
sinfoni.objnod.n_coeffs	objnod-no_coeffs	3
sinfoni.objnod.nord_south_index	objnod-ns_ind	TRUE
sinfoni.objnod.fine_tuning_method	objnod-fine_tune_mtd	P
sinfoni.objnod.order	objnod-order	2
sinfoni.objnod.lower_rejection	objnod-lo_rej	10.0
sinfoni.objnod.higher_rejection	objnod-hi_rej	10.0
sinfoni.objnod.tolerance	objnod-tol	2
sinfoni.objnod.jitter_index	objnod-jit_ind	TRUE
sinfoni.objnod.vllx	objnod-vllx	0
sinfoni.objnod.vlly	objnod-vlly	0
sinfoni.objnod.vurx	objnod-vurx	0
sinfoni.objnod.vury	objnod-vury	0
sinfoni.objnod.fcol	objnod-fcol	0
sinfoni.objnod.sky_cor	objnod-sky_cor	TRUE
sinfoni.objnod.objnod-flux_cor	objnod-flux_cor	TRUE
sinfoni.objnod.objnod-mosaic_max_size	objnod-mosaic_max_size	14196
sinfoni.sinfo_utl_skycor.mask_ws	skycor-mask_ws	1.4
sinfoni.sinfo_utl_skycor.mask_we	skycor-mask_we	2.5
sinfoni.sinfo_utl_skycor.min_frac	skycor-min_frac	0.8
sinfoni.sinfo_utl_skycor.sky_bkg_filter_width	skycor-sky_bkg_filt_width	12
sinfoni.sinfo_utl_skycor.line_hw	skycor-line_hw	4.
sinfoni.sinfo_utl_skycor.scale_method	skycor-scale_method	1
sinfoni.sinfo_utl_skycor.rot_cor	skycor-rot_cor	FALSE
sinfoni.sinfo_utl_skycor.fit_obj_noise	skycor-fit_obj_noise	FALSE
sinfoni.sinfo_utl_skycor.niter	skycor-niter	10
sinfoni.sinfo_utl_skycor.pshift	skycor-pshift	0.0
sinfoni.sinfo_utl_skycor.llx	skycor-llx	1
sinfoni.sinfo_utl_skycor.lly	skycor-lly	1
sinfoni.sinfo_utl_skycor.urx	skycor-urx	64
sinfoni.sinfo_utl_skycor.ury	skycor-ury	64
sinfoni.sinfo_utl_skycor.sub_thr_bkg_from_obj	skycor-sub_thr_bkg_from_obj	FALSE
sinfoni.std_star.switch	std_star-switch	TRUE

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sinfoni.std_star.low_rejection	std_star-lo_rej	0.1
sinfoni.std_star.high_rejection	std_star-hi_rej	0.1
sinfoni.std_star.fwhm_factor	std_star-fwhm_fct	5.0
sinfoni.std_star.conversion_index	std_star-conv_ind	TRUE
sinfoni.psf.switch	psf-switch	TRUE

**Note that to obtain better sky subtraction quality the user should set both the parameters product-density to 3 and the parameter objnod-sky\_cor to TRUE.** The correction of sky residuals should be performed having (at least) a sky frame available. In case a sky frame is missing the pipeline uses the next in time object frame as a “dummy” sky frame and activating the the sky residual correction there is the risk that object lines cancel out after subtraction.

The user should also choose proper values of the critical parameters **skycor-sky\_bkg\_filter\_width**, **skycor-line\_hw**, **skycor-rot\_cor**, **skycor-fit\_obj\_noise**. A check of the results provided by the product table(s) with PRO.CATG QC\_SPECTRA is always recommended to compare the extracted spectra before and after the correction.

This release allows also to indicate the area where the object lies, through the parameters **skycor-llx**, **skycor-ly**, **skycor-urx**, **skycor-ury**. This to allow a more accurate determination of the sky lines residuals and the corresponding spectrum shift with respect to the one of the object in case of low signal to noise target observations. The thermal background emission subtraction can be eventually switched off with the parameter **skycor-sub\_thr\_bkg\_from\_obj**. Having an independent sky-object spectral shift estimation (in pixel units), or willing to overwrite the value computed by the pipeline, the user can set this quantity with the parameter **skycor-pshift**.

This release has the default of the parameter **product-density** set to 2 to make sure that at Paranal the data reduction is fast enough.

## 10.9 sinfo\_rec\_pupil

This recipe performs the same data reduction as the **sinfo\_rec\_jitter** on PUPIL, IMAGE frames. Please refer to [10.8](#) for parameters description. We describe here only the main differences.

### 10.9.1 Input

```
/path_file_raw/SINFO.2004-08-13T03:26:12.559.fits PUPIL_LAMP
/path_file_raw/SINFO.2004-08-13T03:25:30.323.fits PUPIL_LAMP
/path_file_cdb/MASTER_BP_MAP_K_250.fits MASTER_BP_MAP
/path_file_cdb/MASTER_FLAT_LAMP_K_250.fits MASTER_FLAT_LAMP
/path_file_cdb/WAVE_MAP_K_250.fits WAVE_MAP
/path_file_cdb/SLIT_POS_K_250.fits SLIT_POS
/path_file_cdb/SLITLETS_DISTANCE_K.fits SLITLETS_DISTANCE
/path_file_cdb/DISTORTION_K.fits DISTORTION
```

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## 10.9.2 Output

default recipe file name	PRO.CATG	short description	pd
sky00.fits	SKY_STACKED_DUMMY	stacked sky image	2
out_sky_stack_dist0.fits	SKY_STACKED_DIST	stacked sky image distortion corrected	2
out_stack_mflat_dist.fits	MFLAT_STACKED_DIST	stacked master flat image	2
out_stackN.fits	X_CALIBRATOR_STACKED	stacked X image, N=0,1,...	0
out_resampled_obj0.fits	RESAMPLED_OBJ	stacked, resampled object image	2
out_resampled_sky0.fits	RESAMPLED_SKY	stacked, resampled sky image	2
out_resampled_flat0.fits	RESAMPLED_FLAT_LAMP	stacked, resampled flat image	2
		distortions corrected	
out_sky_cube00.fits	OBS_SKY	sky cube	1
out_sky_med00.fits	SKY_MED	SKY_CUBE z-median image	2
out_mflat_cube.fits	MFLAT_CUBE	Master flat cube	2
out_mflat_avg.fits	MFLAT_AVG	MFLAT_CUBE z-mean image	2
out_mflat_med.fits	MFLAT_MED	MFLAT_CUBE z-median image	2
cube_objNN.fits	OBS_X	X STD cube, NN=00,01,...	0
out_objnod.fits	COADD_X	coadded cube	0
out_objnod_med_cube.fits	MED_COADD_X	COADD_X z-median image	0
out_objnod_bpmmap.fits	MASK_COADD_X	COADD_X's mask cube	0
out_ao_performance.fits	AO_PERFORMANCE	table with strehl information	0
out_encircled_energy.fits	ENC_ENERGY	table with encircled energy information	0
out_psf.fits	MASTER_PSF	z-median of COADD_X	0
out_std_star_spectrum.fits	STD_STAR_SPECTRA	table with extracted spectrum, and efficiency information for COADD_X	0
out_starspectrum.fits	STD_STAR_SPECTRUM	collapsed image spectrum COADD_X	0

Here X=PSF or STD or OBJ if in input are PSF or telluric standards or other science frames.

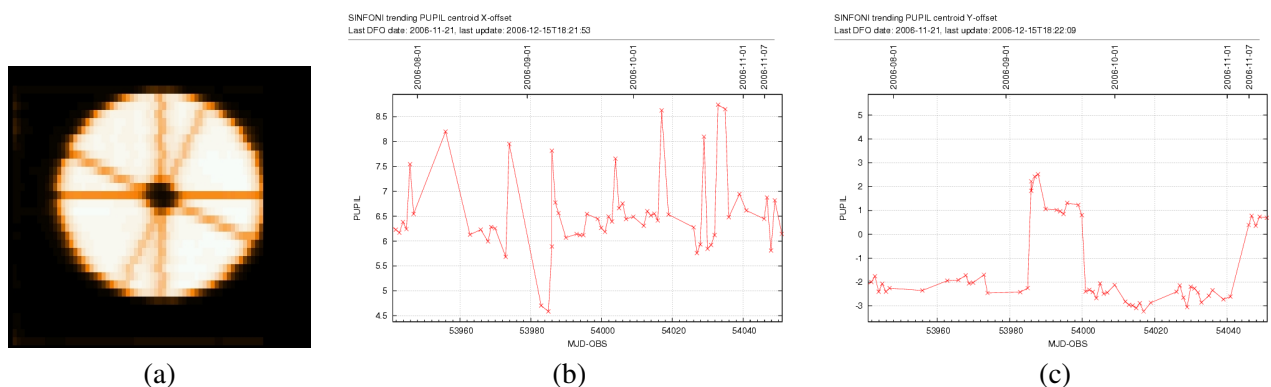


Figure 10.9.1: Telescope pupil centering quality control: (a) pupil image (median of reconstructed cube); (b) trending plot of X centroid shift; (c) trending plot of Y centroid shift.

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### 10.9.3 Quality control

The values of QC.PUPILi.SHIFTX, QC.PUPILi.SHIFTY, indicate the position of the centroid of the pupil image.

### 10.9.4 Parameters

This recipe has the same parameters as the **sinfo\_rec\_jitter** recipe.

## 10.10 sinfo\_utl\_bp\_mask\_add

This recipe performs bad pixel map coaddition.

### 10.10.1 Input

The input files are several (at least 2) bad pixel masks. Their tag should contain the string BP\_MAP.

```
/path_file_cdb/BP_MAP_NL_K_100.fits BP_MAP_NL
/path_file_cdb/BP_MAP_NO_K_100.fits BP_MAP_NO
/path_file_cdb/BP_MAP_HP_K_100.fits BP_MAP_HP
```

### 10.10.2 Output

The output is an image resulting from the logical operator OR applied to all the masks.

### 10.10.3 Parameters

The recipe output filename for the product is bp\_map\_sum.fits

## 10.11 sinfo\_utl\_ima\_arith

This recipe performs image computation.

### 10.11.1 Input

The input files are 2 images and their associated tags should be IMA.

```
/path_file/ima1.fits IMA
/path_file/ima2.fits IMA
```

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### 10.11.2 Output

The output is an image resulting from IMA op IMA where op indicates the operation to be performed. If a numerical value is specified at command line this is subtracted to the first input image.

### 10.11.3 Parameters

parameter	alias	default
sinfo_utl_ima_arith.op	op	+
sinfo_utl_ima_arith.value	value	9999.0

## 10.12 sinfo\_utl\_cube\_create

This recipe builds a cube out of an input raw frame

### 10.12.1 Input

Input are an ON and and OFF frame and the usual master calibration frames input of the jitter recipe:

```
/path_file_raw/SINFO.2004-08-23T09:36:12.316.fits RAW_ON
/path_file_raw/SINFO.2004-08-23T09:51:59.824.fits RAW_OFF
/path_file_cdb/MASTER_BP_MAP_H_250.fits MASTER_BP_MAP
/path_file_cdb/MASTER_FLAT_LAMP_H_250.fits MASTER_FLAT_LAMP
/path_file_cdb/FIRST_COLUMN.fits FIRST_COL
/path_file_cdb/WAVE_MAP_H_250.fits WAVE_MAP
/path_file_cdb/SLITLETS_DISTANCE_H_025.fits SLITLETS_DISTANCE
/path_file_cdb/SLIT_POS_H_250.fits SLIT_POS
/path_file_cdb/DISTORTION_H_025.fits DISTORTION
```

### 10.12.2 Output

The output is a cube with PRO.CATG set to CUBE.

### 10.12.3 Parameters

parameter	alias	default
sinfoni.objnod.jitter_index	objnod-jit_ind	TRUE
sinfoni.objnod.kernel_type	objnod-kernel_typ	tanh
sinfoni.objnod.n_coeffs	objnod-no_coeffs	3
sinfoni.objnod.ns_index	objnod-ns_ind	TRUE
sinfoni.objnod.flux_cor	objnod-flux_cor	FALSE



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sinfoni.objnod.fine_tuning_method	objnod-fine_tune_mtd	P
sinfoni.objnod.order	objnod-order	2

### 10.13 sinfo\_utl\_cube2ima

This recipe performs cube to image conversion.

#### 10.13.1 Input

The input file is a cube. Its tag should be CUBE.

```
/path_file/cube.fits CUBE
```

#### 10.13.2 Output

The output is an image resulting from the average of the cube over a wavelength range which can be set by parameters sinfoni.sinfo\_utl\_cube2ima.ws, sinfoni.sinfo\_utl\_cube2ima.we having aliases '**ws**' and '**we**'. The recipe output filename for the product is out\_ima.fits

#### 10.13.3 Parameters

parameter	alias	default
sinfo_utl_cube2ima.ws	ws	0.9999
sinfo_utl_cube2ima.we	we	2.999

### 10.14 sinfo\_utl\_cube2spectrum

This recipe performs cube to 1D spectrum image conversion.

#### 10.14.1 Input

The input files is a cube Its associated tag should be CUBE.

```
/path_file/cube.fits CUBE
```

#### 10.14.2 Output

The output is an image resulting from the cube manipulated according to the value of the parameter op. over an aperture as specified by the parameter sinfoni.sinfo\_utl\_cube2spectrum.aperture having alias '**op**', '**ap**'.

The recipe output filename for the product is out\_spec.fits

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### 10.14.3 Parameters

Possible operations are: average, clean\_mean, median, sum. If the chosen operation is a clean mean one may define its lower and upper threshold cuts by setting parameters **lo\_rej** and **hi\_rej**. Possible apertures are: rectangle, circle. If the chosen aperture is a rectangle, its corner coordinates can be set with the parameters llx, lly, urx, ury (lower left x,y and upper right x,y). Those parameters follow the C-style convention: arrays start at 0 and end at size-1. If the chosen aperture is a circle, its position and size can be set by the parameters centerx, centery, radius.

parameter	alias	default
sinfo_utl_cube2spectrum.op	op	average
sinfo_utl_cube2spectrum.ap	ap	rectangle
sinfo_utl_cube2spectrum.llx	llx	2
sinfo_utl_cube2spectrum.lly	lly	2
sinfo_utl_cube2spectrum.urx	urx	28
sinfo_utl_cube2spectrum.ury	ury	28
sinfo_utl_cube2spectrum.lo_rej	lo_rej	10
sinfo_utl_cube2spectrum.hi_rej	hi_rej	10
sinfo_utl_cube2spectrum.centerx	centerx	16
sinfo_utl_cube2spectrum.centery	centery	16
sinfo_utl_cube2spectrum.radius	radius	5

## 10.15 sinfo\_utl\_cube\_arith

This recipe performs cube arithmetics. If a parameter value is specified it is assumed that the input frame is a cube with tag CUBE. Else the input files are a cube and an image or a spectrum; their associated tags should be respectively CUBE, IMA or SPECTRUM. The output is a cube (PRO.CATG=CUBE) resulting from the operation CUBE op IMA or CUBE op SPECTRUM or CUBE op value where op indicates the operation to be performed.

### 10.15.1 Input

```
/path_file/cube.fits      CUBE
/path_file/spectrum.fits  SPECTRUM
```

or

```
/path_file/cube.fits      CUBE
/path_file/image.fits     IMA
```

### 10.15.2 Output

The recipe output filename for the product is out\_cube.fits

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### 10.15.3 Parameters

parameter	alias	default
sinfo_utl_cube_arith.op	op	/
sinfo_utl_cube_arith.value	value	99999.0

## 10.16 sinfo\_utl\_cube\_combine

### 10.16.1 Input

The user needs to provide in an input ASCII file the file names of all the cube component to be coadded and their tags (OBS\_OBJ); then to set the recipe input parameter **name\_i** to the filename of another ASCII file specifying the corresponding x and y offsets. The default recipe output filename for the cube product is out\_cube.fits and can be set by the parameter **name\_o**. The name of the corresponding mask is by default out\_maskcube.fits For example if the following list indicates the input cubes (for clarity we indicate also the values of the corresponding offsets, which do not need to appear in the input set of frame)

```
OBS_OBJ1.fits    OBS_OBJ 0.0 0.0
OBS_OBJ2.fits    OBS_OBJ 1.0 -1.0
OBS_OBJ3.fits    OBS_OBJ 2.0 -2.0
```

One needs to set the recipe parameter **name\_i** to the filename of a file with the following content:

```
0.0 0.0
1.0 -1.0
2.0 -2.0
```

The user should read sections [11.1.23](#) and [11.1.24](#) to understand how the size of the coadded cube is determined and how to set proper offset values.

In case a user have observations taken with different templates, each template may have a different reference pointing (usually aligned with the first object frame of the template). The user will first build the cube components and their coadded mosaic corresponding to each template observation using the recipe sinfo\_rec\_jitter.

From release 2.0.0 the sinfo\_utl\_cube\_combine utility has been extended to support also coaddition of cube mosaics. The user will have to determine the proper offset to be applied at each cube mosaic addendum with respect to the first mosaic of the list (taken at reference position X,Y = 0,0) in order to proper coadd the mosaics. In this case the user will assign to each mosaic componed the tag COADD\_OBJ.

Alternatively, to properly combine cube components coming from different templates one needs to compute proper relative offsets in pixel units of each cube with respect to a reference. If the user has for example two data sets, observed with two different templates, one will be used as reference, and the corresponding CUMOFFX/Y keywords will be taken as offset values to be applied to the cube components of that template (we assume here those values are properly set). For the frames of the second teplate, the offsets will be given from the values of the CUMOFFX/Y keywords to which one needs to add the offset in pix units between the reference frames

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observed in the second template and the one of the previous template. This offset can be computed using the INS.TARG.ALPHA|DELTA keywords of the reference frames of the two templates and the pixel scale.

For example if one need to combine the following frames:

```
OBS_OBJ1_set1.fits    OBS_OBJ
...
OBS_OBJN_set1.fits    OBS_OBJ
OBS_OBJ1_set2.fits    OBS_OBJ
...
OBS_OBJM_set2.fits    OBS_OBJ
```

Will set the offsets as:

```
coffx_set1_c1 coffy_set1_c1
coffx_set1_c2 coffy_set1_c2
coffx_set1_c3 coffy_set1_c3
coffx_set2_c1 coffy_set2_c1
coffx_set2_c2 coffy_set2_c2
coffx_set3_c3 coffy_set2_c3
```

where usually `coffx_set1_c1=coffy_set1_c1=0`, `coffx_set1_cn,coffy_set1_cn`,  $n=1\dots N$  are given from the CU-MOFFX/Y keywords of the first set and `coffx_set1_cm, coffy_set1_cm`,  $m=1\dots M$  are given from the CU-MOFFX/Y keywords of the second set plus the offset in pixel between the first frame of the two data sets.

### 10.16.2 Output

The recipe generates the corresponding coadded cube.

### 10.16.3 Parameters

parameter	alias	default
<code>sinfo_utl_cube_combine.name_i</code>	<code>name_i</code>	<code>offset.list</code>
<code>sinfo_utl_cube_combine.name_o</code>	<code>name_o</code>	<code>out_coadd_cube.fits</code>
<code>sinfo_utl_cube_combine.ks_clip</code>	<code>ks_clip</code>	<code>FALSE</code>
<code>sinfo_utl_cube_combine.scale_sky</code>	<code>scale_sky</code>	<code>FALSE</code>
<code>sinfo_utl_cube_combine.xsize</code>	<code>xsize</code>	<code>80</code>
<code>sinfo_utl_cube_combine.ysize</code>	<code>ysize</code>	<code>80</code>

## 10.17 sinfo\_utl\_eff

This recipe calculates efficiency by comparing the appropriately rescaled and atmospheric extinction corrected extracted flux of a SINFONI observation with the flux calibrated one of the same star.

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### 10.17.1 Input

There are two ways to use the recipe - with a star reference table (tag FLUX\_STD\_TABLE) or with a star flux catalog (tag FLUX\_STD\_CATALOG). The sinfo\_utl\_eff.sof file with a star reference table should look like the following:

```
std_star_spectra_J_6_1.fits STD_STAR_SPECTRA
atmoexan.fits EXTCOEFF_TABLE
bd_17d4708_stisnic_002.fits FLUX_STD_TABLE
```

The sof file with an input star flux catalog should look like the following:

```
std_star_spectra_J_6_1.fits STD_STAR_SPECTRA
atmoexan.fits EXTCOEFF_TABLE
std_star_spectra_catalog.fits FLUX_STD_CATALOG
```

Where STD\_STAR\_SPECTRA is the tag corresponding to the FITS file with the extracted SINFONI spectrum (output of sinfo\_rec\_jitter recipe), EXTCOEFF\_TABLE is the tag corresponding to the FITS file describing the atmosphere extinction (provided in the kit release), in two columns “LAMBDA” (Angstrom units) and “LA\_SILLA” (unitless, %), and FLUX\_STD\_TABLE is the tag of the FITS file containing at least the two columns “WAVELENGTH” (in Angstrom units) and “FLUX” describing the analyzed standard star flux calibrated spectrum (to be provided by the user). If FLUX\_STD\_TABLE is not provided, the recipe is looking for a reference data in FLUX\_STD\_CATALOG using the coordinates of the observation (tags RA and DEC in the header) with a tolerance, defined by input parameter "eps". FLUX\_STD\_CATALOG is provided in the kit release.

### 10.17.2 Output

The recipe produces one product with the following table:

column	type	description
WAVELENGTH	double	wavelength from STD_STAR_SPECTRA
EFFICIENCY	double	calculated efficiency

### 10.17.3 Parameters

parameter	alias	default
sinfo_utl_eff.gain	gain	2.42
sinfo_utl_eff.aimprim	aimprim	0
sinfo_utl_eff.eps	eps	0.01

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#### 10.17.4 Expected content of the FLUX\_STD\_TABLE

Column	Type	Units	Description
WAVELENGTH	double	Angstrom	Wavelength
FLUX	double	erg/s/cm**2/A	Flux

PRO.CATG of the output is STD\_EFFICIENCY\_TAB.

### 10.18 sinfo\_utl\_skycor

This recipe allow the user to remove possible residuals of sky lines in the object spectrum. The data reduction performed is described in section [11.1.26](#).

#### 10.18.1 Input

Input are an object cube (OBS\_OBJ, OBS\_STD, or OBS\_PSF) and a sky cube (OBS\_SKY).

#### 10.18.2 Output

Ouput are a sky residual corrected object frame (OBS\_OBJ, OBS\_STD, or OBS\_PSF) and a quality control table (QC\_SPECTRA) containing the following columns:

WAVE	wavelength in Å
INT_OBJ_ORG	original object spectrum
SKY_INT_ORG	original sky spectrum
BKG_INT_FIT	fit of thermal background sky emission
SKY_INT_SMO	smoothed sky spectrum
COR_FCT_VIB	corrective factor to remove contribute from sky lines from vibrational transitions
COR_FCT_ALL	corrective factor to remove contribute from sky lines from vibrational and rotational transitions
INT_OBJ_COR	corrected object spectrum
INT_SKY_COR	corrected sky spectrum

#### 10.18.3 Parameters

parameter	alias	default
sinfoni.sinfo_utl_skycor.mask_ws	skycor-mask_ws	1.4
sinfoni.sinfo_utl_skycor.mask_we	skycor-mask_we	2.5
sinfoni.sinfo_utl_skycor.min_frac	skycor-min_frac	0.8
sinfoni.sinfo_utl_skycor.sky_bkg_filter_width	skycor-sky_bkg_filter_width	12
sinfoni.sinfo_utl_skycor.line_hw	skycor-line_hw	4.0
sinfoni.sinfo_utl_skycor.scale_method	skycor-scale_method	1
sinfoni.sinfo_utl_skycor.rot_cor	skycor-rot_cor	FALSE

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sinfoni.sinfo_utl_skycor.fit_obj_noise	skycor-fit_obj_noise	FALSE
sinfoni.sinfo_utl_skycor.niter	skycor-niter	10
sinfoni.sinfo_utl_skycor.pshift	skycor-pshift	0.0
sinfoni.sinfo_utl_skycor.llx	skycor-llx	1
sinfoni.sinfo_utl_skycor.lly	skycor-lly	1
sinfoni.sinfo_utl_skycor.urx	skycor-urx	64
sinfoni.sinfo_utl_skycor.ury	skycor-ury	64
sinfoni.sinfo_utl_skycor.sub_thr_bkg_from_obj	skycor-sub_thr_bkg_from_obj	FALSE

## 10.19 sinfo\_utl\_skymap

This recipe, used to generate a special bad pixel map input of the SINFONI RTD is used to support Paranal operations. It flags sky lines as bad pixels.

### 10.19.1 Input

Input are sky frames with tag SKY

```
/path_file_raw/SINFO.2004-08-14T08:14:52.101.fits SKY
```

### 10.19.2 Output

The output image, a map of the sky lines, is called out\_skymap.fits

### 10.19.3 Parameters

parameter	alias	default
sinfo_rec_skymap.ysize	ysize	30
sinfo_rec_skymap.xsize	xsize	1
sinfo_rec_skymap.thresh	thresh	30.0

We list here for different pre-optics and bands the suggested parameter values:

grating	scale_out	DIT	scale_in	threshold	window
J	0.025	300	0.1	30.0	30
J	0.1	300	0.1	30.0	30
J	0.25	300	0.25	50.0	30
H	0.025	300	0.1	50.0	30
H	0.1	300	0.1	50.0	30
H	0.25	300	0.25	100.0	30
K	0.025	300	0.1	70.0	30
K	0.1	300	0.1	70.0	30

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K	0.25	300	0.25	200.0	30
H+K	0.025	300	0.1	100.0	30
H+K	0.1	300	0.1	100.0	30
H+K	0.25	300	0.25	300.0	30

## 10.20 sinfo\_utl\_spectrum\_divide\_by\_blackbody

This recipe divides a spectrum by a Black Body spectrum of given temperature.

### 10.20.1 Input

The input file is a spectrum. Its associated tag should be SPECTRUM.

```
STD_STAR_SPECTRUM.fits SPECTRUM
```

### 10.20.2 Output

The output is a spectrum resulting in the division of the input spectrum by a Black Body spectrum of given temperature (parameter '**temp**').

The recipe output filename for the cube product is out\_ima.fits

### 10.20.3 Parameters

parameter	alias	default
sinfo_utl_spectrum_arith.temp	temp	1e+05

## 10.21 sinfo\_utl\_spectrum\_wavelength\_shift

This recipe shift a spectrum in wavelength according to value of the input parameter '**method**'.

### 10.21.1 Input

The input file is a spectrum. Its associated tag should be SPECTRUM.

```
STD_STAR_SPECTRUM.fits SPECTRUM
```

### 10.21.2 Output

The output is a spectrum resulting by a simple wavelength shift (parameter '**shift**').



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The recipe output filename for the cube product is out\_ima.fits

### 10.21.3 Parameters

parameter	alias	default
sinfo_utl_spectrum_arith.method	method	S
sinfo_utl_spectrum_arith.shift	shift	0.1

The spectrum is shifted by shift to sub pixel accuracy resampling the intensity of the pixels using either a spline approximation (**method=S**) or a polynomial approximation (**method=P**).

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## 11 Algorithms and recipe details

In this section we describe the main algorithms implemented in the SINFONI pipeline recipes. Relevant data reduction parameters are typed in **bold** face. For convenience we omit the common prefix **sinfoni.** for the recipe description as well as the step prefix name for the algorithm description.

### 11.1 Algorithms

#### 11.1.1 **sinfo\_rec\_mdark\_detmon**

A master dark is calculated and the clean mean dark level is computed. The master dark is the clean mean of three or more dark frames obtained with the same setup (same DIT, NDIT). This is a pipeline product.

#### 11.1.2 **Read Out Noise determination (common algorithm across pipelines)**

The RON may be measured as the rms on defined areas **dark.llx dark.lly, dark.urx dark.ury**, of the difference between two dark frames, divided by  $\sqrt{2}$ . The RON must be determined independently for each quadrant and port. The RON and its rms are logged as QC parameters: QC.DARK.RON QC.DARK.RONRMS.

Other pipelines (SINFONI, ISAAC, NACO, VISIR) computes the RON by taking all possible consecutive DARK pairs having the same DIT. For each pair the second frame is subtracted to the first one. Then the noise is computed in a region defined by the parameters **ron.llx, ron.lly, ron.urx, ron.ury**, over **nsanp** samples each of size **hsize**, taken randomly in this region. The noise multiplied by  $\sqrt{NDIT}$ , where the NDIT gives the number of DIT repetitions, gives the read out noise.

#### 11.1.3 **Histogram computation**

This algorithm build an histogram of the input frame intensity values. Input parameters are the minimum and maximum allowed frame intensity values, **histo\_min, histo\_max** in order to remove the contribution of threshold pixels, and the number of histogram sampling points **histo\_npoints**. The interval [**histo\_min, histo\_max**] is divided in equal steps of size  $\frac{histo\_max - histo\_min}{histo\_npoints}$ , and an histogram of the frame intensity values is build. The histogram maximum and its corresponding bin is determined (this is the frame intensity clean mean). Then a Gaussian is fit to the histogram. The Gaussian sigma gives the frame intensity clean sigma. To make the fit more robust one may fit the logarithm of the intensity as a function of the square of the histogram frequency (abscissa). This is a linear function and the corresponding fit should be quite robust and reliable.

#### 11.1.4 **PTC and MED Algorithms for Gain computation**

To measure the detector's gain, a single algorithm is implemented common to both optical and infrared wavelength domains. In optical and infrared domain, the input is different. In the following description what we indicate as *off* frame is in the near infrared an off-lamp frame, but in the optical domain is a bias frame.

Input frames for NIR are a set of pairs of on/off flats, each set with a different DIT.

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If we indicate with  $on_{dif}$  the on frames difference:

$$on_{dif} = on_2 - on_1 \quad (1)$$

If we indicate with  $of_{dif}$  the off frames difference:

$$of_{dif} = of_2 - of_1 \quad (2)$$

If we indicate with  $mon_i$  the on frame clean mean (obtained either with the algorithm 11.1.3 or with the algorithm 11.1.6) relative to the integration time (EPTIME or DIT)  $i$ :

$$mon_i = mean(on_i) \quad (3)$$

And with  $mof_i$  the similar off frames clean mean:

$$mof_i = mean(of_i) \quad (4)$$

One may find the gain by fitting the following linear (one may even fit a parabola and verify that the coefficient of the quadratic term is small enough, this being a QC parameter) relation:

$$(mon_1 + mon_2) - (mof_1 + mof_2)_i = gain(e^-/ADU)(\sigma_{ondif}^2 - \sigma_{ofdif}^2)_i \alpha \quad (5)$$

where  $\alpha$  is the autocorrelation function computed as:

$$\alpha = \sum_{m,n} R_{m,n} \quad (6)$$

where:

$$R_{m,n} = \frac{\sum_{i,j} V_{i,j} * V_{i+m,j+n}}{\sum_{i,j} V_{i,j}^2} \quad (7)$$

where  $V_{i,j}$  is the intensity of the pixel  $(i, j)$ .

The values of  $mon_1$ ,  $mof_2$ ,  $mof_1$ ,  $mof_2$ ,  $\sigma_{ondif}^1$ ,  $\sigma_{ondif}^2$  from equation 5 together with the values of the frame exposure time (DIT or EXPTIME) for each frame set should be logged in the corresponding columns of the product table having PRO.CATG set to GAIN\_INFO.

If the parameter **method** is set to PTC (Photon Transfer Curve method) the gain is obtained with a linear fit of the values in eq. 5. Else, if the **method** is set to MED, the gain is obtained computing a simple median of the gain values that can be obtained with equation 5.

$$conad = gain^{-1} \quad (8)$$

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The gain and its error are computed and logged as QC parameters (QC GAIN, QC GAIN MSE, in  $e^-/\text{ADU}$  and QC CONAD in  $\text{ADU}/e^-$ , QC AUTCORFA).

In eq. 5 it is critical to compute a clean mean and a clean standard deviation. Two methods are possible:

1. Build a histogram and compute the histogram centre and sigma (11.1.3).
2. Determine the mean and standard deviation repeating **niter** a clean mean computation with kappa-sigma cleaning of bad pixels (11.1.6).

### 11.1.5 Detector linearity computation (IR): irplib\_detmon\_nir\_linear

The input interface is the same to irplib\_detmon\_gain, that is, for each exposure time value two pairs of frames (a pair ON and a pair OFF) are provided. The input frames DPR keyword should be (we recommend the following, but each instrument pipeline may decide to adopt also different values):

DPR CATG	DPR TECH	DPR TYPE
CALIB	IMAGE	LINEARITY,FLAT,DETCAR

For each exposure time value, two difference frames are computed:  $dif_1 = on_1 - of_1$  and  $dif_2 = on_2 - of_2$ . These two difference frames are then averaged pixel by pixel. Then the mean and the median values of the difference frame in a rectangle defined by **llx**, **lly**, **urx** and **ury**, are computed and written in the output table (PRO.CATG=LIN\_INFO), in the column MEAN and MED, together with the corresponding pair integration time (DIT or EXPTIME), and the corresponding ratio, MEAN\_DIT and MEAN\_DIT.

Each average frame corresponding to a given DIT value is stored in a different plane of cube. Then for each x,y pixel intensity  $I(x,y,t)$  is computed a polynomial fit of order **order** in direction t.

$$Q(x, y, t) = \sum_{1, \text{order}} c_i(x, y) t^i \quad (9)$$

$$Q'(x, y, t) = \frac{Q(x, y, t)}{c_1(x, y) t} \quad (10)$$

The corresponding coefficients  $c_i$  are stored in a cube of size **order**. This is a recipe product (LIN\_COEF). From each cube plane are computed the corresponding medians and standard deviations. Those values are used to identify bad pixels (threshold pixels, trap columns, dead pixels, non linear pixels, noisy pixels). Bad pixels are flagged and stored in a corresponding bad pixel map. The median and standard deviation computation is repeated to remove the contribution of bad pixels. Finally the median and standard deviation of each coefficient plane are monitored as quality control parameters (QC LIN COEFi, QC LIN COEFi ERR).

$$Q(t) = \sum_{1, \text{order}} c_i t^i \quad (11)$$

$$Q'(t) = \frac{Q(t)}{c_1 t} \quad (12)$$

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Alternatively the detector linearity may be monitored on the frame obtained by integrating the signal over a user defined (**llx**, **lly**, **urx**, **ury**) detector region.

For each input frame on-off pair the difference frame is computed:  $dif = on - of$ . Each frame difference is stored on an imagelist. Then the clean mean/median and standard deviation are computed on a given frame region (**llx**, **lly**, **urx**, **ury**). Those values are computed for each frame difference and stored in a vector. Then computed a polynomial fit of order **order** of vector values is computed:

$$P(t) = \sum_{1, \text{order}} a_i t^i \quad (13)$$

$$P'(t) = \frac{P(t)}{a_1 t} \quad (14)$$

The corresponding coefficients  $a_i$  are monitored as quality control parameters (QC LIN COEFi, QC LIN COEFi ERR).

Note that  $Q'(t)$  (or  $P'(t)$ ) is independent from the lamp flux.

The correction that can be applied in a later step of the cascade would be:

$$I_{corrected} = I_{original} / Q'(t) \quad (15)$$

A map of deviating pixels is also generated. Those pixels are the one which deviate by more than **kappa** sigma by the fit, where sigma is the standard deviation of the points from the fit.

Indeed several bad pixel masks can be obtained: A map of threshold pixels (pixels with intensities beyond a given **threshold**). A map of dead pixels (pixels for which the  $c_0$  - or the corresponding pixel intensity - is below a minimum threshold **threshold\_min**). A map of trap pixels (pixels for which  $c_0$  deviates more than **kappa**\*sigma by the median of  $c_0$ ). A map on non linear pixels (pixels which deviates more than **kappa**\* sigma from the linear behaviour-or pixels whose  $c_1$  deviates more than **kappa** \*sigma from the median of  $c_1(x, y)$ ). A map of non quadratic pixels (pixels which deviates more than **kappa**\* sigma from the quadratic behaviour-or pixels whose  $c_2$  deviates more than **kappa**\*sigma from the median of  $c_2(x, y)$ ).

An additional QC parameter is QC LIN EFF, the effective non-linearity correction at a reference user defined level **ref\_level**:  $Q'(\text{ref\_level})$ .

#### 11.1.6 Iteratives clean mean and sigma computation

This algorithm computes a clean mean and standard deviation through iterative kappa-sigma clipping of outliers. At each iteration the value of the clean mean and sigma is updated. Optionally the user may set the minimum and maximum allowed intensity values (**threshold\_min**, **threshold\_max**). Initially the input frame intensity values outside the interval [**threshold\_min**, **threshold\_max**] are flagged to remove their contribute from the following operations. Then an initial value of the intensity mean and stdev are computed. A loop is repeated **niter** iterations, and in each iteration are clipped intensity values which are outside the interval [mean-**kappa**\*stdev, mean+**kappa**\*stdev]. The final values of mean and stdev are the clean frame intensity mean and sigma.

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### 11.1.7 Frame stacking

The input image frames are stacked to build a cube. Each plane of the cube corresponds to an input image.

### 11.1.8 Average with rejection

In this document we use often the terminology *clean mean*, *clean average*, or *average with rejection*. With those terms we mean that it is computed a mean of a list of values by avoiding outlier values like for example bad pixels, and therefore, this operation yields a better SNR than a simple mean. In case the values to be averaged are pixels intensities of several images stacked in a cube, the mean along the z axis of the cube is computed at each x,y pixel after having rejected the intensity values which lie outside an interval [**low\_rejection**,**high\_rejection**].

### 11.1.9 Detector non linearity computation

- Method 1

From the input set of raw flat frames, “off” and “on” frames are extracted and put in two sets. A pair of “on” and “off” frames with same DIT is selected from each set. Then, for each frame pair  $i$ , the ratio  $med\_dit_i$  is computed as:

$$med\_dit_i = \frac{median(frm_{on}(i)) - median(frm_{off}(i))}{DIT(i)}$$

And the mean of all  $N$   $med\_dit_i$  values is computed as:

$$mean = \frac{\sum_i^N med\_dit_i}{N}$$

A parabolic fit of the product of  $DIT(i) \times mean$ , as a function of  $med\_dit(i)$ , is performed.

The non linear coefficient of the fit is the detector non linearity parameter.

- Method 2

The input flat field frames with in/decreasing intensity are stacked in a cube and for each pixel position the dependence of each plane pixel intensity with respect to the whole plane clean average intensity is determined. This curve is fit with a polynomial of order **order**. In the stacking process low and high intensity pixels may be rejected by properly setting the parameters **low\_rejection** and **high\_rejection**. A clean mean of all polynomials is computed. The pixels whose intensity constant ( $coef_0$ ) or slope ( $coef_1$ ) coefficients exceed the mean by **thresh\_sigma\_factor** times the standard deviation of the pixel intensity are rejected. Pixels whose non quadratic coefficient exceeds **non\_lin\_threshold** are rejected.

Thus a map of the pixels which do not have a linear sensitivity is generated, together with a table containing the polynomial coefficients: the non-linear terms give an estimate of the detector non-linearity.

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### 11.1.10 Nearest neighbours bad pixel cleaning

This method is applied in the recipes `sinfo_rec_mflat` and `sinfo_rec_distortion` to clean the bad pixels of a flat frame. The algorithm is controlled by the parameters **method\_index** and **factor**, and, if **method\_index** is 4, the bad pixel cleaning is repeated **iterations** times.

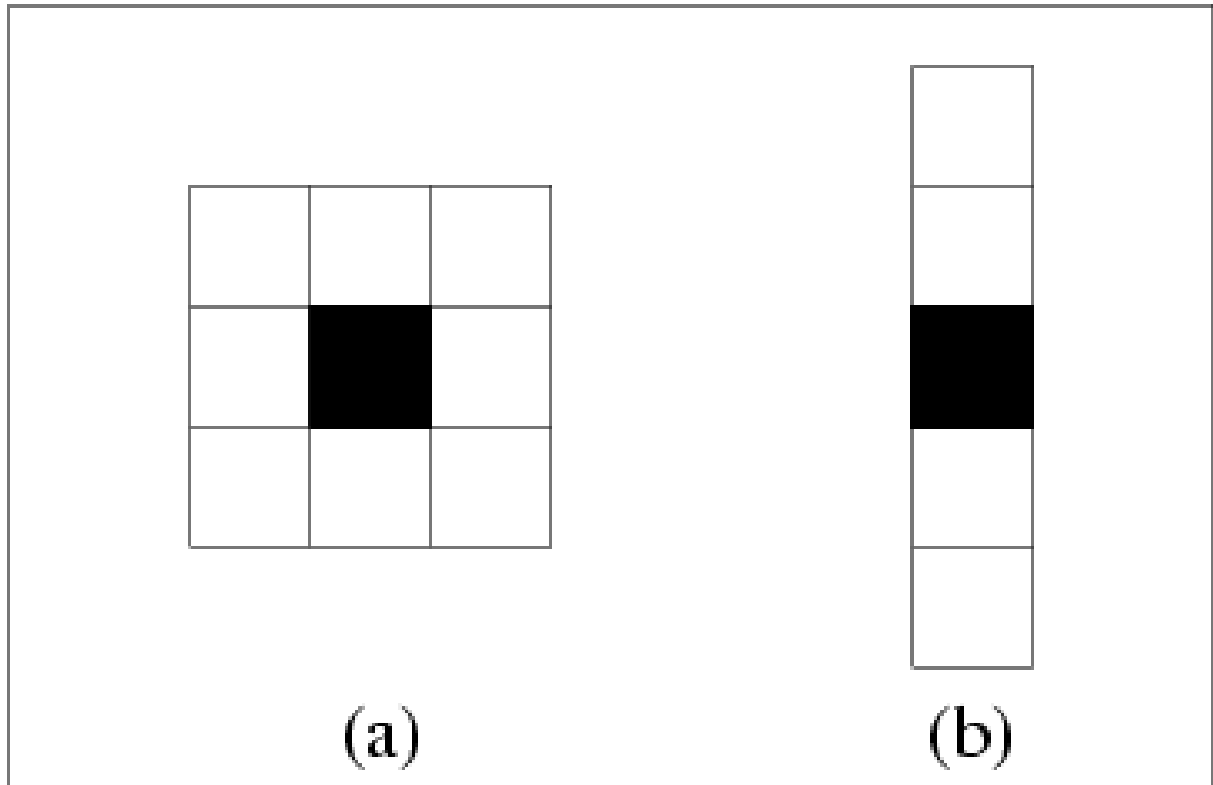


Figure 11.1.1: A bad pixel is indicated in black. If **method\_index** is 1,2 or 4 this is corrected by evaluating the eight nearest neighbours pixel intensities (a). If **method\_index** is 3, the four closest pixels along the dispersion direction are considered (b).

- If **method\_index** is 1, for each image pixel intensity,  $I_i$ , the eight nearest neighbours pixels intensities,  $I_j$ , are considered and the corresponding median,  $median_i$ , is computed excluding from this set those pixels whose intensity is NAN.

$$median_i = median(I_j) \dots I_j \neq NAN$$

- If the parameter **factor** is set to zero:

$$I_i = median_i$$

- If the parameter **factor** is negative:

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$$I_i = \begin{cases} median_i & \text{if } \|I_i - median_i\| > -factor \\ I_i & \text{else} \end{cases}$$

– If the parameter **factor** is positive:

$$I_i = \begin{cases} median_i & \text{if } \|I_i - median_i\| > factor \times \sqrt{median_i} \\ I_i & \text{else} \end{cases}$$

- If **method\_index** is 2, the absolute distances  $dist_i$  of the eight nearest neighbours pixels  $j$  are computed for each bad pixel  $i$  as:

$$dist_i = \frac{\sqrt{\sum_{j=1}^8 (I_i - I_j)^2 * w_j}}{\sum_{j=1}^8 w_j}$$

where

$$w_j = \begin{cases} 0 & \text{if } I_j = NAN \\ 1 & \text{else} \end{cases}$$

The median distance and its standard deviation are then computed as:

$$median\_distance = median(dist_i)$$

$$stdev = \sqrt{(\sum_i dist_i^2) - (\sum_i dist_i)^2}$$

– If the parameter **factor** is zero:

$$I_i = dist_i$$

– If the parameter **factor** is negative:

$$I_i = \begin{cases} dist_i & \text{if } \|median\_distance - dist_i\| > -factor \times stdev \\ I_i & \text{else} \end{cases}$$

– if the parameter **factor** is positive:

$$I_i = \begin{cases} dist_i & \text{if } \|median\_distance - dist_i\| > factor \times stdev \sqrt{dist_i} \\ I_i & \text{else} \end{cases}$$

- If **method\_index** is 3, the intensities of the four closest pixels in spectral direction are considered and their mean intensity is computed for each bad pixel  $i$  as:

$$mean_i = \frac{\sqrt{\sum_{j=1}^4 (I_i - I_j) * w_j}}{\sum_{j=1}^4 w_j}$$

where

$$w_j = \begin{cases} 0 & \text{if } I_j = NAN \\ 1 & \text{else} \end{cases}$$



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- If the parameter **factor** is zero:

$$I_i = mean_i$$

- If the parameter **factor** is negative:

$$I_i = \begin{cases} mean_i & \text{if } \|I_i - mean_i\| > -factor \\ I_i & \text{else} \end{cases}$$

- If the parameter **factor** is positive:

$$I_i = \begin{cases} mean_i & \text{if } \|I_i - mean_i\| > factor \times \sqrt{mean_i} \\ I_i & \text{else} \end{cases}$$

- If **method\_index** is 4, the local clean (**low\_rejection**, **high\_rejection**) standard deviation *clean\_stdev* in a box (**llx**, **lly**, **urx**, **ury**) is computed. Then the difference of the pixel and the median of the nearest neighbours is computed by using the eight closest pixels of every pixel.

$$median_i = median(I_j) \dots I_j \neq NAN, j = 1 \dots 8$$

- if the parameter **factor** is zero:

$$I_i = median_i$$

- if the parameter **factor** is negative:

$$I_i = \begin{cases} median_i & \text{if } \|I_i - median_i\| > -factor \times clean\_stdev \\ I_i & \text{else} \end{cases}$$

- if the parameter **factor** is positive:

$$I_i = \begin{cases} median_i & \text{if } \|I_i - median_i\| > factor \times \sqrt{\|median_i\|} \\ I_i & \text{else} \end{cases}$$

The previous operations are repeated for (**iterations**) times to be able to consider small clusters of bad pixels.

### 11.1.11 Detector gain computation

The gain is computed as part of the recipe `sinfo_rec_detlin`.

Pairs of consecutive off-flats (be those `frm_off1` and `frm_off2`) and pairs of consecutive on-flats (be those `frm_on1` and `frm_on2`) are selected from the input data frames and their difference is computed ( $diff\_frm_{on} = \overline{frm_{on2}} - \overline{frm_{on1}}$  and  $diff\_frm_{off} = \overline{frm_{off2}} - \overline{frm_{off1}}$ ). Then the mean of each frame ( $\overline{frm_{on1}}$ ,  $\overline{frm_{on2}}$ ,  $\overline{frm_{off1}}$ ,  $\overline{frm_{off2}}$ ) and the standard deviation of the difference  $stdev(diff\_frm_{on})$  and  $stdev(diff\_frm_{off})$  are computed.

Finally the gain is given by:

$$gain = \frac{(\overline{frm_{on1}} + \overline{frm_{on2}}) - (\overline{frm_{off1}} + \overline{frm_{off2}})}{(stdev(diff\_frm_{on})^2 - stdev(diff\_frm_{off})^2)}$$

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### 11.1.12 Read Out Noise computation

All possible consecutive pairs having the same DIT are extracted from the input set of frames. For each pair the second frame is subtracted from the first one. Then the noise is computed in a region defined by parameters **xmin**, **xmax**, **ymin**, **ymax**, over **nsamp** samples each of size **hsize** taken randomly in the given region. The noise multiplied by  $\sqrt{NDIT}$ , where NDIT the number of DIT repetitions, gives the read out noise.

### 11.1.13 Fixed Pattern Noise computation

The FPN is computed in the same way as the RON but it is applied to a master dark/flat. The factor  $\sqrt{NDIT}$  does not apply.

### 11.1.14 Line position determination

The locations of the arc lamp lines are determined on an arc lamp frame, input of the recipe `sinfo_rec_wavecal` or `sinfo_rec_distortion`.

- For each detector column, an initial guess wavelength is assigned to each detector row pixel by using the pixel row value and the input initial guess value for the starting wavelength, (**begin\_wave**), the linear and quadratic terms of the dispersion (**guess\_disp1** and **guess\_disp2**) at the given instrument setting (see Figure 11.1.2 (a)). Then the detector rows corresponding to each entry of the reference line list are identified. Line positions and intensities given by the reference line table are assigned to those columns. A delta-shaped spectrum is obtained in this way. This spectrum is convolved with a Gaussian profile of given **sigma** (see Figure 11.1.2 (a)). A pixel shift is obtained by correlating this artificial line spectrum with the arc lamp frame spectrum. The correlation takes into account only those lines whose intensity is greater than a threshold set by parameter **min\_diff**. Thus one obtains approximate values (with accuracy of the order of a pixel) for the position and the wavelength assigned to each image position.
- To determine the dispersion relation (see 11.1.15) more accurately the recipe selects and uses only line identifications whose distance from the nearest neighbour is greater than **half\_width** pixels.
- The recipe finally determines several lists of line positions:
  - a line list of row indices for the line positions;
  - a clean list of well separated line positions;
  - a list of wavelengths corresponding to the raw positions;
  - a list of wavelengths corresponding to the clean raw positions.

Those lists allow to associate each emission line in each spectrum with an approximate pixel position and the exact wavelength.

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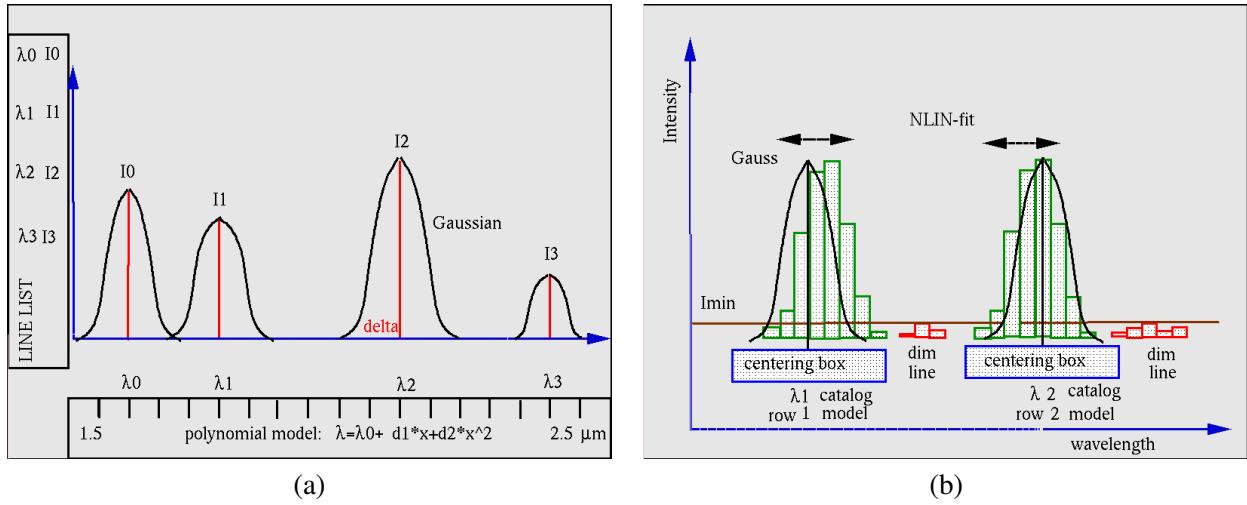


Figure 11.1.2: Wavelength calibration: (a) Using a polynomial model and guess values for the instrument setting central wavelength, the first and second order dispersion coefficients, it is built a syntetic spectrum by associating to each reference catalogue entry a delta profile with proper wavelength and intensity and then by convolving this with a Gaussian profile of proper FWHM; (b) With a non linear fit of a Gaussian to each detector line having an intensity above a given threshold, the fit being limited to box of a given size in wavelength centered to each line position previously determined, the position of each line is refined.

#### 11.1.15 Dispersion relation and wavelength map determination

- A Levenberg-Marquardt fit of a Gaussian profile of given **fwhm** is performed considering the raw positions which lie in regions defined by boxes of half-size **half\_width**, each centered at the line positions determined by the algorithm described in 11.1.14. The fit is restricted to the lines whose intensity is greater than **min\_amplitude** with respect to the background. This fit allows to determine each line position with sub pixel accuracy (see Figure 11.1.2 (b)).
- Detector defects may lead to erroneous line detections. To prevent these misidentifications the fit is limited to lines which lie no more than **pixel\_tolerance** pixels from the corresponding position, obtained assuming a linear dispersion **guess\_disp1** model. Possible outliers are flagged by setting the line-position parameter of the fit to zero.
- For each image column, a polynomial fit of degree **n\_a\_coefficients** and coefficients  $acoe f_k$  is performed, so as to determine the dispersion relation between the listed wavelength values  $\lambda(j)$  and the Gauss-fitted positions  $y\_pos(j)$  for each image column using the singular value decomposition method.

$$\lambda(j) = \sum_{k=0}^{n\_a\_coefficients} acoe f_k * y\_pos(j)^k$$

Data points which lie beyond **max\_residuals** pixels from the corresponding fit value are rejected. In the fit each data point is weighted by a factor proportional to the product of the guess dispersion value **guess\_disp1** and the error associated with each position point from the previous Gaussian fit.

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- Then the positions of the slitlet edges are determined. Offset coefficients  $acoeff_o$  resulting from the polynomial fit for adjacent columns are compared. When they differ by more than **pixel\_dist\*guess\_disp1**, it is assumed that this is due to the crossing of a slitlet's edge. Here **pixel\_dist** indicates the minimal distance in pixels between adjacent slitlets measured along the wavelength direction. This provides a first approximation of the slitlets' edges.
- A clean average of the coefficients is determined by rejecting the extreme 10% low and high values and performing a kappa-sigma clipping, where the constant kappa is set by **sigma\_factor**.
- Then a singular value decomposition fit of the polynomial coefficients is performed across the spatial extent of each slitlet using a polynomial of low degree **n\_b\_coefficients** and the smoothed polynomial coefficients  $\overline{acoeff_{i,x}}$  are computed anew.
- Finally a wavelength map is built by associating with each image pixel a wavelength corresponding to the value resulting from the polynomial fit of degree **n\_a\_coefficients**. The intensity  $I_{map}(x, y)$  at each image point  $x, y$  is given by

$$I_{map}(x, y) = \lambda(x, y)$$

where:

$$\lambda(x, y) = \sum_{i=0}^{n\_a\_coefficients} \overline{acoeff_{i,x}} \times (y - off)^i$$

and

$$off = \frac{(ny - 1)}{2}$$

where  $ny$  is the number of rows of the image.

#### 11.1.16 Line shift computation

The recipe searches for the five brightest lines in each column of the input arc lamp. The shift between each line position on the frame and the one resulting from the polynomial dispersion relation of degree **n\_a\_coefficients** obtained in 11.1.15 is computed. Finally the overall wavelength calibration error is computed as the clean average of the shifts obtained after removing 10% of the outliers. Then the wavelength positioning error at different wavelengths is computed in a similar way. This value is monitored for quality control.

#### 11.1.17 Dispersion relation adjustment

If a dispersion relation and a wavelength map are already available one may still want to adjust them to properly match the given arc lamp frame.

The positions of the slitlets' edges are initially determined by checking that the values of the zero order coefficient  $acoeff_0$  for adjacent image columns differ by more than **guess\_disp1 × pixel\_dist**.

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An artificial spectrum is generated by convolving each entry of the reference line list with a Gaussian of position and intensity as given by the reference line table and a sigma equal to  $(\text{mag\_factor} - 1)^2$ .

Bad and negative pixels are filtered out from the input image and a low-pass filter of half width **mag\_factor** is applied. The resulting cleaned and smoothed image is convolved with the artificial spectrum to compute their shift, the maximum of the correlation value and the position at which this maximum is reached.

A new value of the zero order dispersion coefficients  $acoe f_0$  is determined. A clean mean is performed on the dispersion coefficients  $acoe f_k$  and new values for the clean dispersion coefficients  $\overline{acoe f_k}$  are determined with a single value decomposition fit over each slitlet spatial domain.

Finally a new wavelength map is generated using the clean dispersion coefficients  $\overline{acoe f_k}$  as described at the end of section 11.1.15.

### 11.1.18 Slitlet position computation

In order to be able to reconstruct the original observed image out of the raw image the positions of the edges of each slitlet must be determined accurately. The 32 slitlets must be stacked one on top of the other by using accurate reference positions, otherwise the resulting image rows would be shifted with respect to the others yielding weird images.

To determine the slitlets positions an exposure of an arc lamp is used. The slitlets edges are clearly visible if looking at a bright, stand-alone emission line (for example see Figure 7.2.1 (d)). Such an emission line can be used to determine the absolute positions of the left and the right edge of each slitlet using a non-linear least square fit of an appropriate fitting function.

Two methods are possible to determine the slitlet positions. They differs only for the choice of the fitting function.

Initially the brightest lines are searched in the image column domain corresponding to the first slitlet. From this list the lines which have a bright neighbour within **y\_box** pixels are filtered out. Then a first estimate of the slitlet edges is performed: a slitlet edge is reached when the first (offset) dispersion coefficient  $coe f_0$  has a variation greater than **y\_box**. Those values are checked to remove misidentifications possibly due to bad pixels.

Then the image intensity values of the maxima reached in each slitlet are determined by searching in rectangular boxes centered at each slitlet positions  $edge(j)$  each of size **y\_box** along the spectral direction, and size  $edge(j) - edge(j-1) + 2 \times \text{box\_length}$  along the spatial direction.

In case the user sets the parameter **wcal-estimate\_ind** value to TRUE the search of the image intensity maxima is limited to the interval **[lo\_pos,hi\_pos]** along the spectral direction.

The minimum value of the maxima is determined to have an initial value of the background intensity at which a slitlet edge detection should be triggered. The list of maxima is divided in two sets and on each data set a least square fit is performed with an appropriate fitting function.

The Edge method uses in the non-linear fit a linear step function that means a linear function between two positions with two constant backgrounds to the left and to the right of the slitlet positions. Free parameters of the fit are the two positions of the left and right background values. The mean of both fitted positions is used as resulting left or right slitlet edge position.

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The Boltzmann method uses as fitting function a sigmoidal Boltzmann function, which describes the transition between two values:

$$y = \frac{A_1 - A_2}{1 + \exp \frac{x-x_0}{dx}} + A_2$$

where  $A_1$  is the left background value,  $A_2$  is the right background value,  $dx$  is the width of the transition region and  $x_0$  is the center of the transition region (turning point of the function). Free parameters of the fit are both the background values, the width  $dx$  and the center  $x_0$ , which is then used as left or right slitlet edge position.

### 11.1.19 Slitlet distances computation

The slitlet distances are computed on a frame which is the result of an average with rejection performed on several (usually 75) fibre frames. Each frame has the first column of a few slitlets illuminated by the light coming from a fiber.

For each raw of the stacked frame the following operations are performed:

- The pixel positions whose intensity is greater than three times the mean of the image are determined on the stacked, distortion corrected, fibre frame. This generates for each fibre of the input frame a set of columns where the intensity is greater than the mean of the frame.
- The intensity maximum of each column is accurately determined by comparing image pixel intensities in a spatial range of size **half\_width** centered at each column position of the found set. Possible wrong column detections, due to bad pixels, can be flagged by verifying that the found position has a value which differs from the one of the previous slitlet by **estimated\_dist** with a tolerance **dev\_tol**.
- A least square fit with a Gaussian function of FWHM **fwhm** is performed to precisely locate the fibres and thus determine the slitlet positions.

In this way one determines for each image raw the slitlets' positions and can build their relative difference. Making a mean of those relative distances along the spectral direction, excluding instances for which the relative distance differs from the **estimated\_distance** by more than **dev\_tol**, one finally finds 31 values of the relative slitlet distances.

### 11.1.20 Optical distortions computation

The distortion function, which characterises the curvature of the spectral traces of the 32 slices, is calculated from a series of continuous light fibre spectra taken with the fibre moved perpendicularly to the slices. For every position of the fibre a raw FITS data file is recorded. With an initial data reduction step the single fibre spectra are co-added to an all-fibers synthetic frame and the offset of the first slitlet is calculated as a reference position. The distortion is computed in three further steps (see Figure. 11.1.3):

- Detecting the fibres and tracing the curved fibre spectra.

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- Constructing two numerical grids on the distorted and the undistorted fibre positions.
- Solving a 2D polynomial fit to transform positions from raw to undistorted coordinates.

Finally, the recipe determines the position of the edges of the slitlets by fitting the edges of the brightest arc line of each slitlet with a linear step function or a Boltzmann function.

### 11.1.21 Cube construction: resampling

The algorithm described below is executed by recipe `sinfo_rec_jitter`. Given a source image and a corresponding wavelength calibration file, an image is produced in which elements in a given row are associated with a single wavelength. In this way the wavelength shifts between adjacent elements in the rows of the input image are corrected. The output image in the wavelength domain is larger than the input image. Due to the brick wall pattern of the raw frames, some pixels in the first and last few rows have undefined values that are flagged by setting them to NAN (see Figure. 11.1.4)

The distribution of these undefined values varies from column to column. The input image is resampled at discrete wavelength intervals using a polynomial interpolation of degree `n_coeffs`. Different values of the wavelength sampling size and the central wavelength are used for each observed band. Thus, each row has a defined wavelength for each observed band.

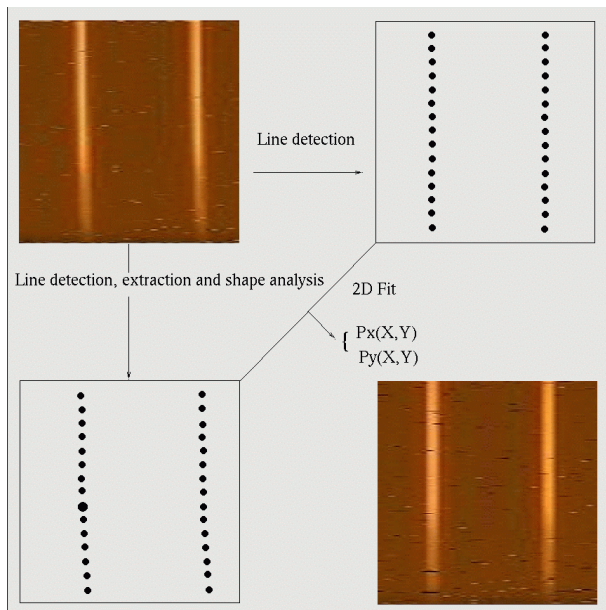


Figure 11.1.3: This image describes the concept of the distortion computation algorithm. The spectra of the fibres are traced, two grids on the distorted and undistorted space are built, then a 2D polynomial transformation is performed. This figure displays only two of the 32 slitlets.

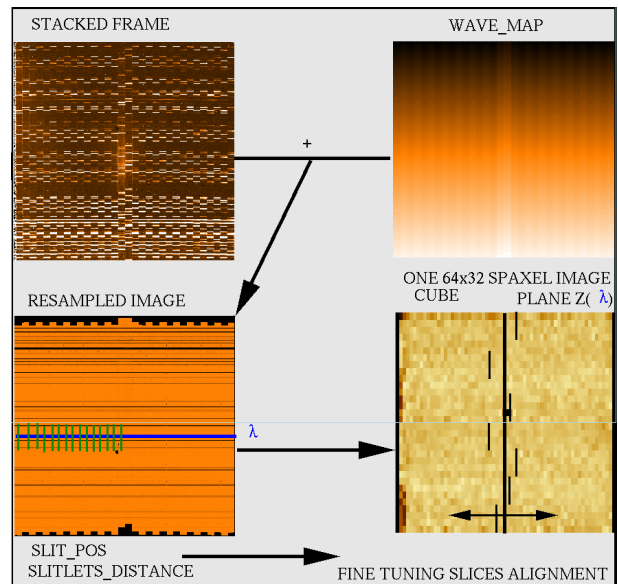


Figure 11.1.4: Cube reconstruction: raw data are resampled using a wavelength map to remove the brick-wall pattern. The slitlets are then stacked into a cube taking slitlet distances and edge positions into account. Each plane of the cube is a monochromatic image of the instrument FOV.



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Since each frame row is now associated with a defined wavelength, each row is used to construct an image which has a defined wavelength. This is done by stacking 32 slitlets on each other, of which each consists of 64 spatial pixels (called also spaxels). Due to the fact that the slitlets length is not exactly 64 pixels and the distance between slitlets is not exactly 64 pixels the edge positions of the slitlets must be known to sub-pixel accuracy (see 11.1.18). Furthermore, the slitlets must be sorted in the correct sequence (see Figure 4.1.2 (bottom) or Figure 7.1.1 (b)) to get the correct sequence of the rows in the final images.

The centers of each slitlet on the resampled image are determined by averaging the edge positions of the slitlets computed as described in 11.1.18 to get the center positions. Then the centers of the slitlets on the raw image are adjusted on the centers of the corresponding rows of the stacked data cube images. Since only integer pixels can be used a sub-pixel error is made at centering, which is stored and used to shift the rows in the reconstructed images of the data cube to the correct sub-pixel position using a user definable method (**objnod-fine\_tune\_mtd**). As the edges of the left-most or right-most slitlets may be too near to or fall outside the image margins, then the fitting of the edges may fail. Then the slitlets distances determined as described in 11.1.19 must be used to accurately align each slitlet in the final reconstructed image plane.

### 11.1.22 Cube coaddition

Each cube component is vignetted chopping out from each cube plane left as many pixels as specified by parameters **vllx**, **vllx**, **vurx**, **vury** (defaulted to 0, 0, 0, 0). As consequence of this the actual corner coordinates of each cube plane being coadded are:

$$llx = 1 + vllx \qquad lly = 1 + vllx \qquad urx = 64 - vurx \qquad ury = 64 - vury$$

If **sky\_scales** == TRUE, before cube coaddition, the spatial median of each cube plane is subtracted from each contributing cube plane to remove sky background residuals possibly not corrected in the previous data reduction steps (e.g. during the frame stacking), for example due to sky variations with time.

Each target object offset is determined by reading the HIERARCH ESO CUMOFFSETX/Y FITS keywords. The exposure time corresponding to each target acquisition is read from the FITS header. Then the recipe computes the minimum size of the cross section along the z-axis of a parallelepipedus which cover the full observed field of view and determines the offsets to apply to each cube component to properly merge them in the coadded cube.

In this manual the 3D frame obtained after cube coaddition is often called cube for simplicity.

Then each contributing cube plane is shifted to locate it in its proper position in the coadded cube. Each pixel intensity of the coadded cube has an intensity given by the weighed mean of the intensities of each corresponding overlapping pixel from the contributing cubes, the weight being given by the exposure time of each target frame.

If **ks\_clip** == TRUE, in the cube coaddition step a kappa-sigma clipping of the contributing overlapping pixels intensities is performed using a user defined value of **kappa**.

### 11.1.23 Mosaic cube size determination

The size of the cube mosaic is determined as follows. The recipe make reference to the values of the FITS keywords SEQ.CUMOFFSETX/Y (later for brevity CUMX/Y), or to the values set by the user if the utility



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sinfo\_utl\_cube\_combine is used. The minimum and maximum values of CUMX/Y are determined. The mosaic center position is determined as:

$$\begin{aligned}
offx_c &= (offx_{min} + offx_{max})/2 \\
offy_c &= (offy_{min} + offy_{max})/2 \\
size_x &= 2 * floor(offx_{max} - offx_{min} + 0.5) + size_{x_{min}} \\
size_y &= 2 * floor(offy_{max} - offy_{min} + 0.5) + size_{y_{min}}
\end{aligned}$$

where  $size_{x_{min}}$  and  $size_{y_{min}}$  the minimum X and Y sizes of the input cubes (eventually mosaic) components.

#### 11.1.24 Cubes alignment

To properly align and coadd object cubes observed with different telescope pointings the recipe make reference to the values of the FITS keywords CUMX/Y, or to the values set by the user if the utility sinfo\_utl\_cube\_combine is used. The recipe uses as reference the CUMX/Y values of the first object cube of the list. Then are computed the relative differences:

$$\begin{aligned}
diffx_i &= cumx_i - cumx_{ref} \\
diffy_i &= cumy_i - cumy_{ref}
\end{aligned}$$

Then to each cubes is assigned the following offset:

$$\begin{aligned}
offx_i &= \begin{cases} +2 * diffx_i & \text{if mjd_obs} > 53825 \text{ (1st April, 2006)} \\ -2 * diffx_i & \text{if } 53421.58210082 < \text{mjd_obs} \leq 53825 \\ -2 * diffx_i & \text{else} \end{cases} \\
offy_i &= \begin{cases} +2 * diffy_i & \text{if mjd_obs} > 53825 \text{ (1st April, 2006)} \\ +2 * diffy_i & \text{if } 53421.58210082 < \text{mjd_obs} \leq 53825 \\ -2 * diffy_i & \text{else} \end{cases}
\end{aligned}$$

The utility sinfo\_utl\_cube\_combine uses user defined offsets following the same conventions. This means that assuming the coordinate values in the FITS header are not correct only of a small quantity, the user may apply the corresponding correction by applying the correct change to the values set in the FITS header.

#### 11.1.25 Estimation of the sky from object frames in case the input set is missing sky frames

Since it is possible that there is no time for the acquisition of sky frames when executing a science OB, it is necessary to provide a proper algorithm capable of providing a good estimate of the sky.

The SINFONI pipeline supports three methods, each corresponding to different values of the parameter **aj\_method**. If **aj\_method** is 0 no sky is estimated and thus no sky is subtracted. If **aj\_method** is 1, then for each object observation the algorithm uses the object exposure with the closest MJD-OBS as an approximation of a sky exposure. If **aj\_method** is 2 the sky is given by a median of all the contributing objects.

Provided that the target object positions in the acquired frames are separated by at least three times the FWHM of the object, the data reduction scheme implemented for the case **aj\_method**=1 should provide an accurate sky

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estimation. If this is not the case the user may set **aj\_method** to 2 or try to subtract the sky before data reduction and then reduce the sky-subtracted data as science object frames choosing **aj\_method=0**.

If **aj\_method** is 1 each contributing cube (and the coadded cube) will show regions with negative intensity.

If **aj\_method** is 1, **ks\_clip** == TRUE, and each contributing frame fills most of the FOV (for example because the chosen camera scale is 25 mas) the user may have to use a value of **kappa** greater than the default, which is set to 2, to prevent that some object point is clipped, which could result possibly in local spikes in the object spectrum.

### 11.1.26 Sky residual correction

More details on the algorithm to remove residual OH emission from near infrared spectra may be found in [18].

In this release the pipeline can correct for improper sky subtraction; in older releases this caused residuals in on-off sky-subtracted frames. The sky emission is removed from the object observation by subtracting the sky frame from the object frame. This assumes that the two frames have a stable spectral format. However, it has been found that in on-off, object-sky sequences the instrument setting can occasionally have instabilities up to a significant fraction of a pixel. The residual sky features (resembling a P-Cygni profile) can be significantly reduced by using an improved data reduction procedure developed in collaboration with Richard Davies from MPE (Figure 11.1.5, right panel and 11.1.6).

Near infrared airglow emission originates in OH radicals which are created by reactions between ozone and hydrogen high in the atmosphere. Removing the emission lines which result from the subsequent radiative cascade is a crucial part of processing near infrared (1-2.5  $\mu\text{m}$ ) spectra.

This problem is relevant as it has been proven that the strongest OH lines, which lie in the H band, have fluxes of the order of  $400 \text{ phs}^{-1} \text{ m}^{-2} \text{ arcsec}^{-2}$ . This contrasts strongly with the background continuum measurable between lines of only  $590 \text{ phs}^{-1} \text{ m}^{-2} \text{ arcsec}^{-2} \mu\text{m}^{-1}$ . This means that even at a moderate spectral resolution  $R \approx 3000$ , like the one of SINFONI, the background level on an OH line can be more than three orders of magnitude higher than that between them.

Due to temporal changes in the absolute flux in OH sky lines exposure times are usually limited to 2-3 minutes. This sets a lower limit to the statistical photon noise. An additional source of problems is the peculiar change of absolute flux in OH lines. Finally the effects of instrumental flexures, which are typical of instrument rotation in a Cassegrain or Nasmyth telescope configuration, may lead to P-Cygni type residuals.

While long-slit spectrographs, using a slit length much longer than the object of interest may allow to prevent such problems after performing an appropriate fit of the residual sky background, in integral field spectrographs like SINFONI, the typically very limited FOV, impose constraints on the observations and to devise appropriate data reduction techniques.

We describe here an algorithm, first proposed by Richard Davies [18], and implemented in the SINFONI pipeline with a few modifications, introduced for robustness purposes.

In a nutshell the algorithm allows one to find a scaling as function of wavelength that can be applied to a spectrum from a sky cube in order to match it optimally to the sky background in an object cube. This scaling function is then applied separately to the spectrum at each wavelength position of the sky cube, creating a modified sky cube. This modified cube is then subtracted from the object cube.

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The scaling function may be found by taking into account that the main contributors to the OH lines is coming from vibrational and rotational transitions, with the first kind contributing the most. Transitions between vibrational bands lie within well defined wavelength limits, and it is only small the amount of overlap between different vibrational transitions. Thus, to a first approximation one may divide the spectrum into sections corresponding to specific vibrational transitions and treat these separately.

The sky residual correction algorithm follows the following steps:

- The wavelength ranges to which correspond the different vibrational and rotational transitions which originate the OH emission lines are defined. The full wavelength range over which to perform the operations involved in the sky lines residual correction can be defined setting parameters **skycor-mask\_ws** and **skycor-mask\_we**.
- The noise associated to the object frame is calculated.
  - It is determined the histogram of the object intensity values.
  - The histogram distribution is selected to the region nearby the histogram's peak.
  - The histogram distribution center and its width are found: the center is initially the abscissa value at which the distribution reach its maximum. The width is half of the distance between the center and the abscissa at which the histogram has a minimum. if the parameter **skycor-fit\_obj\_noise** is set to TRUE those values are refined with a Gaussian fit.
- Object intensities more than two times the object's noise above the background are flagged.
  - From the object cube and from the flagged object cube are extracted points having wavelengths values within the merged range corresponding to the OH vibrational transitions previously defined.
  - For each cube's spectra at a given point x,y, are computed the number of object pixels with finite values and the number of flagged pixels and their ratio. If the number of object pixels with finite values is greater than half of the spectral pixels, the given point x,y is considered a good one and the corresponding pixel in a ratio image is set equal to the value of the ratio previously computed.
  - If the number of good pixels is less than one it is issued an error.
- Sky pixels are identified, flagged, and selected as good sky pixels when they make up at least a given fraction (this can be defined by the user modifying the value of the parameter **skycor-min\_frac** which is set by default to (80%) of the spectrum.
  - It is computed the ratio of good image pixels divided by the total number of the image pixels.
  - If this ratio is less than a given threshold ratio **skycor-min\_frac** (80%) a new selection of object good pixels is performed to increase this number to the threshold ratio.
- The average object and sky spectra are calculated. For each plane in the cube (both object and sky) an average is computed by excluding pixels which are more than three sigmas above the median. This defines the object and sky intensity. The parameters **skycor-llx**, **skycor-lly**, **skycor-urx**, **skycor-ury**, allow the user to specify the position where the object is supposed to be in each cube plane. This may allow a more accurate determination of the sky lines residuals and the corresponding spectrum shift with respect to the one of the object.

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- The thermal contribution to the sky background is estimated and subtracted from the sky spectrum.

If **skycor-sub\_thr\_bkg\_from\_obj** is set to TRUE the sky background is subtracted from the object spectrum.

If **stack-sub\_raw\_sky** is set to TRUE (sky frame subtraction from the object, as by default), **skycor-sub\_thr\_bkg\_from\_obj** should be set to FALSE.

Viceversa if **stack-sub\_raw\_sky** is set to FALSE, **skycor-sub\_thr\_bkg\_from\_obj** should be set to TRUE.

To improve accuracy, as the sky spectrum contains many emission lines, we first smooth this spectrum with a running box and then fit a Boltzmann function (see Fig. 11.1.5, left panel).

- Initially the sky spectrum is smoothed on a window of size (**skycor-sky\_bkg\_filter\_width**).
- Then the smoothed spectrum is fit by a Boltzmann temperature distribution:

$$fac(\lambda, T) = \frac{1}{\lambda^5} \frac{1}{\exp(\frac{c}{\lambda \cdot T}) - 1}$$

where  $c = 14387.7$ ,  $\lambda$  is the wavelength in  $\mu\text{m}$  and  $T$  is the temperature in K. Are calculated the minimum and maximum values of this distribution,  $fac_{min}$  and  $fac_{max}$ .

- For robustness are selected sky spectrum points with intensity greater than -2. This selection is done to prevent contributions from negative region of the sky spectrum, possibly occurring in the case the sky frame is approximated by the closest object frame in the observation sequence, as in the case in which no sky frame is observed in the same template (or no sky frame is provided in the set of frames). Then are furtherly selected sky points whose intensity is different from the median by less than ten sigmas.
- A Levenberg-Marquardt fit of the Boltzmann distribution:

$$B = a_0 * a_1 * fac(\lambda, T)$$

is performed to this selected sky spectrum. The fit is repeated **skycor-niter** times to get three-digit accurate values of the Boltzmann temperature and the constants  $a_0$  and  $a_1$ .

- If the fit fails (this may happen sometimes in case of a very flat sky spectrum), a simple uniform fit of the sky spectrum is performed.
- Finally the fitted thermal background is subtracted from the sky spectrum.
- To properly compute the shift between object and sky only wavelengths corresponding to vibrational or rotational transitions are considered. This removes the effect from improper spectrum features.
- The pixel shift between the sky and the object spectra is computed by cross correlating the two spectra and the sky spectrum and the sky cube are correspondingly shifted.
  - It is computed the mean of the sky spectrum intensity. If the mean is negative the spectrum is flipped.
  - Too low sky intensities are flagged.
  - Line picks are identified.
  - A Gaussian fit centered at each line pick is performed to compute the line wavelength position of the object and the sky lines, the line object and sky intensity and its associated error. Only lines of width greater than **skycor-line\_hw** are considered.

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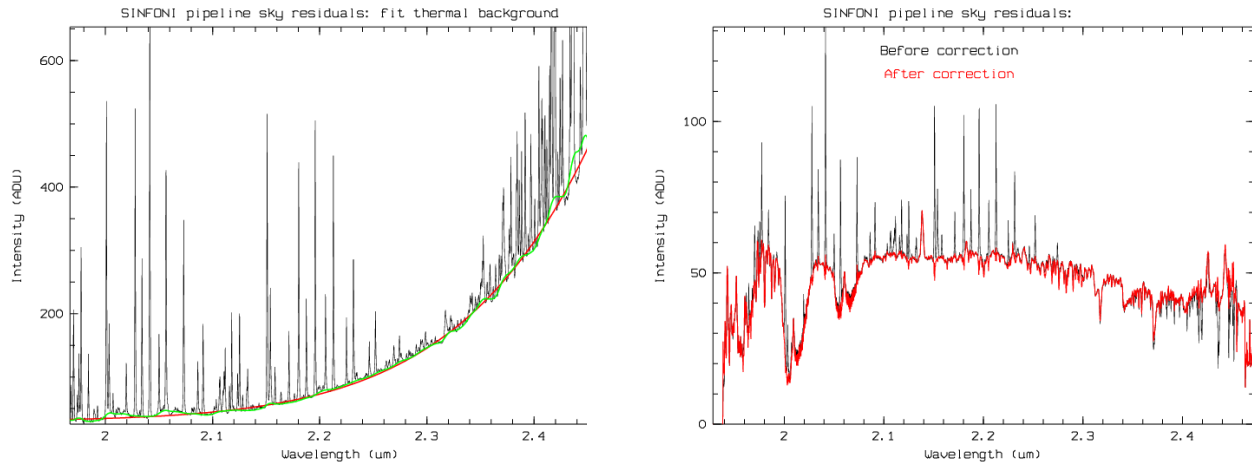


Figure 11.1.5: The fit of a sky spectrum is shown on the left panel. The sky background (black) is first smoothed (green) and then fit by a Boltzmann function (red). On the right panel we compare un-corrected (black) and corrected (red) sky subtracted object spectra. Rotational transitions affect the spectrum quality by only 1-5%. Not only can one see 1-0S(1) at 2.12  $\mu\text{m}$  and Br $_{\gamma}$  at 2.17  $\mu\text{m}$ , but now the H2 1-0Q(1) and 1-0Q(3) emission lines are clearly seen longward of 2.4  $\mu\text{m}$ , and several CO band-heads are also visible at 2.3-2.4  $\mu\text{m}$ .

- A kappa sigma clipping of the differences of the line positions as determined in the object and in the sky spectrum is performed.
- A uniform function is fit to the residual line position differences.

If the user has estimated the sky-object spectral shift independently, or would like to overwrite the value computed by the pipeline, can set this quantity (in pixel units) with the parameter **skycor-pshift**.

- The sky spectrum and the sky cube are correspondingly shifted.
- The scaling factor that is applied to the sky emission lines in order to remove them from the object spectrum is computed.

The object and sky sub-spectra are extracted over a wavelength range corresponding to each vibrational transition. For each wavelength range:

- Are used only pixels where the spectrum is finite.
- Sky lines are identified. Line and continuum regions are disentangled.
- If the line and continuum regions contain enough points ( $2 \times \text{skycor-line\_hw}$ ) it is computed the line ratio between object and sky line spectra. Two methods are possible: amoeba fit (**skycor-scale\_method=0**) or maximum likelihood (**skycor-scale\_method=1**). After a first line ratio computation it is performed a kappa sigma clipping of spectrum outliers, and eventually the fit is repeated.

In this way it is computed a wavelength dependent scaling factor. In first approximation, this factor is derived from the line contributions only due to vibrational transitions.

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If the parameter **skycor-rot\_cor** is set to TRUE, then the recipe computes a scaling factor based on the contribution of the rotational transitions. Later the two factors are combined and the shifted sky spectrum is accordingly rescaled and subtracted from the object spectrum, to obtain an object spectrum cleaned of sky lines (see Fig. [11.1.5](#), right panel).

- The shifted and scaled sky cube is finally subtracted from the object cube. The resulting cube is thus corrected for the sky residuals (see Fig. [11.1.6](#), right panels).

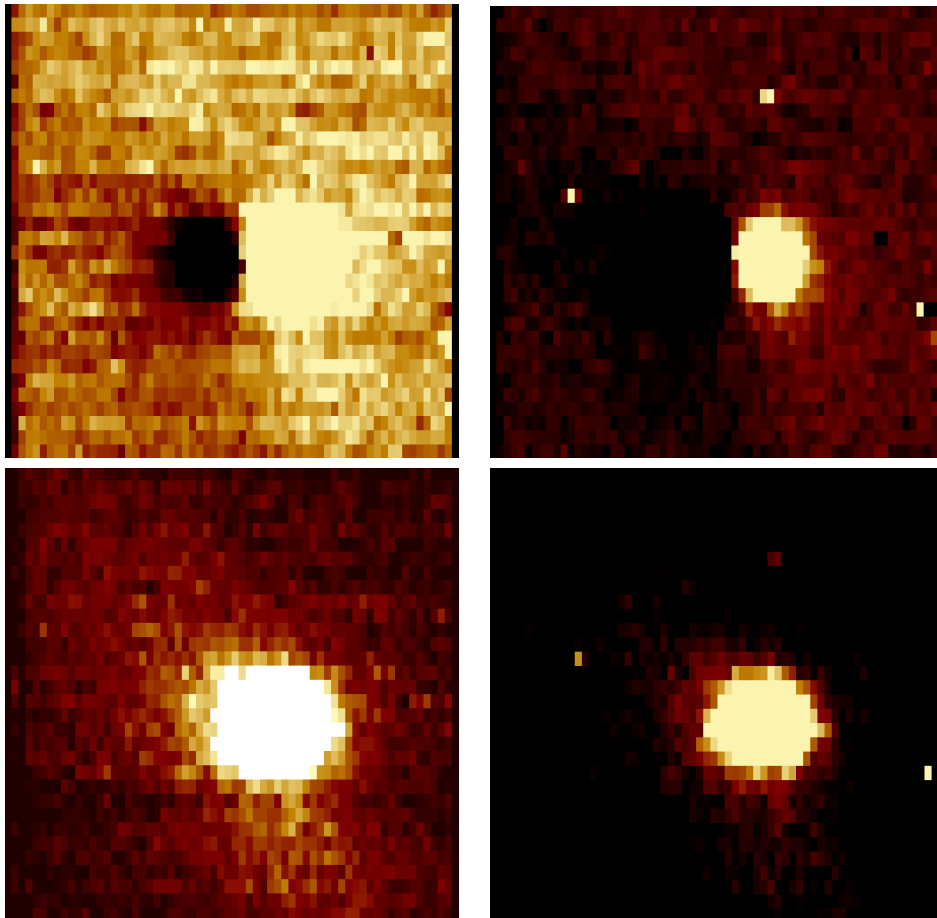


Figure 11.1.6: Comparison between un-corrected (left) and corrected (right) object cubes. On the top are displayed the cube plane corresponding to  $2.151 \mu\text{m}$  for a case in which no sky frame is present in input. On the bottom are displayed the cube plane corresponding to  $1.915 \mu\text{m}$  for a case in which a sky frame is present. Images on the left have the same intensity scale of images in the right.

### 11.1.27 Efficiency computation

The estimation of the efficiency, i.e. the throughput of the atmosphere+telescope+instrument, is described in this section.

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**Method used in sinfo\_utl\_eff recipe** The efficiency at a given wavelength  $\lambda$  is computed as:

$$EFF(\lambda) = \frac{COUNTS\_BKG(\lambda) \cdot 10^{0.4 \cdot PEXT(\lambda) \cdot (AIRPRIM - AIRMASS(\lambda))} \cdot GAIN \cdot PEPH(\lambda)}{EXPTIME \cdot TEL\_AREA \cdot PREF(\lambda)} \cdot factor$$

Where  $COUNTS\_BKG(\lambda)$  is the extracted standard star spectrum as observed by SINFONI, corrected for the contribute from the sky background, at a given wavelength  $\lambda$ ,  $PEXT(\lambda)$  is the atmospheric extinction value,  $AIRMASS(\lambda)$  is the airmass at which the object (star) was actually observed,  $AIRPRIM$  is a parameter to indicate if the efficiency is be computed at airmass=0 (no-atmosphere) or at a given value (usually the one at which the reference standard star spectrum may be tabulated).  $GAIN$  indicates the SINFONI detector's gain (assumed to be 2.42), and  $PEPH(\lambda)$  is the energy of one photon ( $PEPH(\lambda) = \frac{10^7}{\lambda \cdot 1.986 \cdot 10^{19}} \cdot J \cdot um^{-1}$ ),  $EXPTIME$  is the total exposure time in seconds,  $TEL\_AREA$  is the UT telescope collecting area ( $51.2 \cdot 10^4 \cdot cm^2$ ),  $PREF(\lambda)$  is the flux calibrated spectrum of the reference source.  $factor$  is a multiplicative number that corrects for the fact that in the previous formula some quantity has been expressed in different units.

**Standard method** In order to use in operations the previously described method the pipeline requires as input a catalog of standard star fluxes observed during SINFONI operations. We are in the process of building it. Thus it is still valid at this stage to evaluate the efficiency using the following, less accurate method (that assumes the observed standard star emits like a black body).

1. The flux on the detector is converted to units of ergs/s/cm<sup>2</sup>/Å for a star with 0<sup>th</sup> magnitude. The quanta are photons.
  - The following operations are applied to the wavelength-calibrated, extracted spectra. The signal is integrated over an area of five FWHM of the input source PSF to ensure that all the light is included.
  - This spectrum is rescaled by
    - (a) dividing by the DIT,
    - (b) dividing by the surface area, A, of M1 in cm<sup>2</sup>,
    - (c) multiplying by the Gain (2.42),
    - (d) multiplying this by the flux ratio of the observed star and a 0th magnitude star, i.e.  $10^{\frac{Mag}{2.5}}$ ,
    - (e) dividing by the dispersion (Å per pixel),
    - (f) multiplying by the energy of the photon ( $\frac{hc}{\lambda}$ ).

This corresponds to multiplying the spectrum by the following factor:

$$\frac{gain \times 10^{\frac{Mag}{2.5}}}{DIT \times A \times Dispersion} \times \frac{hc}{\lambda}$$

where the following numerical values for the physical constants are used:

h = 6.62618e-34 Js (Planck constant)

c = 2.998e8 m/s (Speed of Light)

k = 1.3807e-23 J/K (Boltzmann constant)

2. The recipe computes the theoretical spectrum of a 0<sup>th</sup> magnitude star in units of ergs/s/cm<sup>2</sup>/Å.

The following method is inaccurate for spectral types that are not A0V.



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- The ratio between the flux from a blackbody at wavelength  $\lambda$  and the flux from the blackbody with  $T=10,000$  K at wavelength  $\lambda_c$  is computed.
- This curve is scaled so that the value at the central flux is  $f_0$ , where  $f_0$  is for a 0th magnitude star in J, H, K and "HK":

band	$\lambda_c$ ( $\mu\text{m}$ )	$f_0$ (ergs/s/cm <sup>2</sup> /Å)
J	1.225	3.11e-10
H	1.675	1.15e-10
K	2.175	4.10e-11
HK	1.950	8e-11

A more accurate method is described in the following and needs to be implemented.

- The spectral type of the star is determined looking into a catalogue.
  - From this information is obtained the star energy distribution.
  - This curve is scaled so that the value at the central flux is  $f_0$ .
3. The result of step 1 is divided by the one from step 2. This is the efficiency.

### 11.1.28 Strehl computation

The central maximum in units of the total flux of a PSF is a measure of the image quality and AO performance. The Strehl ratio is the observed ratio in units of theoretically possible (diffraction limited) ratio. It is a number usually between  $\simeq 0.01$  (seeing limited) and 0.6-0.8 depending on the performance and the ambient conditions.

As the SINFONI possible FOV are either too narrow or too large for most of the calibration stars used to measure the instrument Strehl, it has been defined a special template in which the same PSF standard is observed first in the 0.025 mas scale, to accurately determine the object image Point Spread Function maximum, and then with the 0.100 mas scale to determine the star flux and sky background levels.

Normally the Strehl is determined as ratio:

$$Strehl = \frac{I_{max}/flux}{PSF_{max}/flux_{PSF}}$$

Where  $I_{max}$  is the maximum intensity of the object (sky background subtracted), and  $flux$  the corresponding flux, while  $PSF_{max}$  is the maximum intensity of a corresponding theoretical PSF corresponding to a telescope with the same diameters for the primary and secondary mirrors, at a given wavelength and in a given wavelength range, at a given pixel scale, with a given size.

This formula is applied on both images of the PSF standard taken with two camera pixel scales (25 and 100 mas).

The SINFONI pipeline implements the same algorithm as in the Paranal Multi Strehl Meter GUI.

Initially it is performed a 2D Gaussian fit to the image resulting averaging the STD star cube along the wavelength (z) axis. This fit determines the approximate position of the STD star image, the FWHM along the major



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and minor axes and the orientation of the elliptic isophotes. Then the sky background is subtracted by taking the median value of the four image plane's corner regions,  $8 \times 8$  pixels each. Finally it is determined the maximum of the resulting sky corrected image.

The star flux is defined as the flux of the STD star above the sky background.

Then it is built the instrument PSF by taking into account also of the possible anamorphysm and occultation introduced by the secondary mirror and the PSF's maximum and flux are determined.

### 11.1.29 Standard star position detection

The recipe `sinfo_rec_jitter` determines the position of the maximum in the image obtained by collapsing the cube along the z-axis. Then the STD star object (which is assumed to be the only object in the FOV) is more accurately located using a centroid algorithm assuming a 2D Gaussian shape approximation for the object PSF, which also allows to estimate the STD star FWHM along the X and Y directions.

### 11.1.30 Atmospheric refraction algorithm

**Creating the calibration table** The shift in the North-South direction as a function of airmass and wavelength is computed on a set of standard stars observations for each band (J, H, K, H+K) and spatial scales (25, 100, 250) (See Fig.11.1.7).

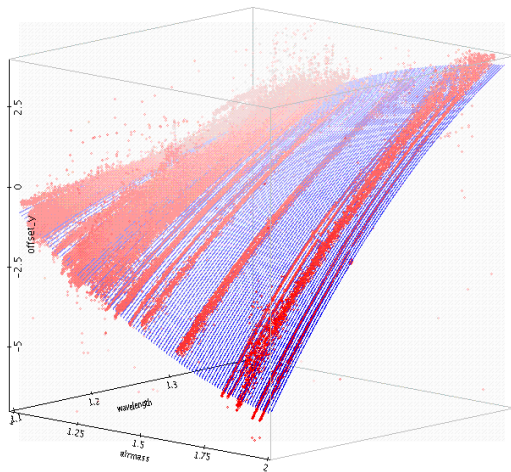


Figure 11.1.7: Offset by North-South direction (red) and the polynomial fit (blue) (J band, 0.25 mas).

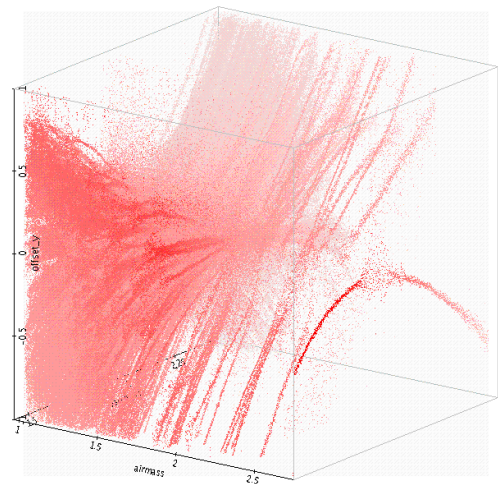


Figure 11.1.8: Offset by Y (North-South) direction in HK band 250 spatial scale

The corresponding shifts measured for each cube plane along the EAST-WEST direction have values mostly in the range  $(-0.25, +0.25)$  pixels as shown by Fig.11.1.9.

The computation of the shift in the North-South direction is done for each plane by the 2D Gaussian fit of the object PSF on the intermediate cubes and is a function on NORTH-SOUTH direction angle (ABSROT START

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and ABSROT END parameters in the fits header). The coefficients of the corresponding 2D polynomial fit are saved into a calibration table (for example ATM\_REF\_CORR\_025\_H.poly.fits, and in similar tables for other bands and spatial scales).

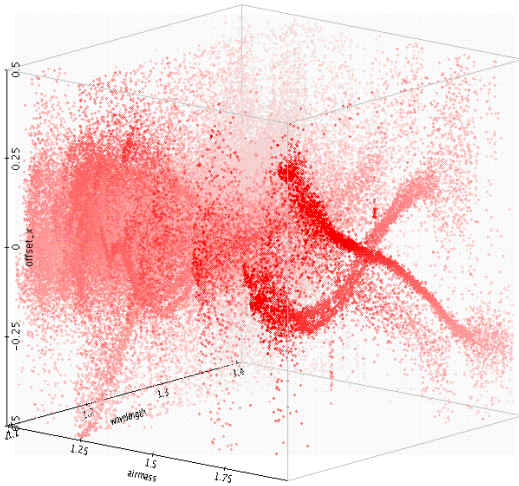


Figure 11.1.9: Offset by East-West direction (J band, 0.25 mas), the main cloud within the -0.25 +0.25 range

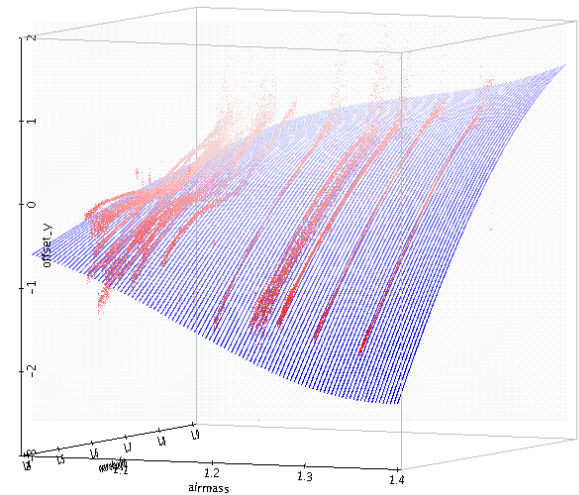


Figure 11.1.10: Offset by North-South direction (red) and the polynomial fit (blue) (H band, 0.25 mas)

For the 250 mas scale this calibration procedure is very complex, because of large fluctuations of the offset in the North-South direction (See Fig. 11.1.8), and anyway the shift in pixels is of the order of 1 spatial bin.

**Size of the each intermediate cube** is 64 x 64 pixels. In our dataset we have observed the shift could be up to 7 pixels (J Band, 25 mas). The current implementation can lead to a usually small loss of some information at the edge of some planes after correction (usually at the beginning and the end of the wavelength range), as we decided to keep the cube size fixed. A solution of this not very frequent problem may be require over-sizing each cube component but would require changing the mosaic reconstruction algorithm, and imply as a side effect larger and unpredictable data storage. For this reason we think the implementation done is sufficient to cover most of user's cases.

### 11.1.31 Encircled energy computation

The encircled energy is the signal integrated in a given area centered on the position where the object reaches its maximum. For this computation it is critical to estimate the flux of the background.

### 11.1.32 Spectrum extraction

The standard star spectrum is extracted by summing the object signal in each plane of the cube. The residual sky background contribution is given by the constant term of a 2D Gaussian fit of the image obtained by averaging

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the cube along z, in a range of **factor** times the mean FWHM ( $\text{FWHM}=0.5*(\text{FWHM}_X+\text{FWHM}_Y)$ ) of the observed standard star.

## 11.2 Recipes

### 11.2.1 Detector linearity and non-linear bad pixel map determination: `sinfo_rec_detlin`

The `sinfo_rec_distortion` recipe computes the detector non-linearity coefficient as described in 11.1.9 (using methods 1 and 2). The detector gain is also computed as described in 11.1.11. In this way several pieces of information are generated: a table with information on detector non-linearity (obtained with method 1), a table with information on the gain, a cube with the coefficients of a polynomial fit to each pixel intensity which provides pixel-by-pixel information on the detector non-linearity, a bad pixel map with non-linear pixels (the last two products are obtained as described using method 2 as described in 11.1.9).

### 11.2.2 Detector linearity and gain computation: `sinfo_rec_lingain`

We remind the user to 11.1.5 and 11.1.4.

### 11.2.3 Master dark and bad pixel map determination: `sinfo_rec_mdark`

A set of input raw dark frames is stacked in a cube. An average with rejection (parameters **`bp_noise.low_rejection`** and **`bp_noise.high_rejection`**), yields a *mean* and a standard deviation, *stdev*. Pixels which deviate from the *mean* more than a user defined factor (**`dark.threshold_sigma_factor`**) times the *stdev* are flagged as bad pixels. This results in a bad (hot) pixel map which flags pixels with a high dark current.

A set of input raw dark frames is sorted according to DIT thus generating corresponding groups. Then an average with rejection (controlled by parameters **`dark.low_rejection`** and **`dark.high_rejection`**) is computed within each group of frames. This results in a master dark frame for each DIT.

On each possible pair of consecutive raw frames the read-out noise is determined in a region defined by the parameters **`dark.qc_ron_xmin`**, **`dark.qc_ron_xmax`**, **`dark.qc_ron_ymin`**, **`dark.qc_ron_ymax`**, and using **`dark.qc_ron_nsamp`** random samples each of size **`dark.qc_ron_hsize`** as described in 11.1.12. On the master dark the fixed pattern noise is determined in two regions defined by the parameters **`dark.qc_fpn_xmin`**, **`dark.qc_fpn_xmax`**, **`dark.qc_fpn_ymin`**, **`dark.qc_fpn_ymax`**, using **`dark.fpn_ron_nsamp`** random samples each of size **`dark.fpn_ron_hsize`** as described in 11.1.13.

### 11.2.4 Master dark determination: `sinfo_rec_mdark_detmon`

We remind the user to 11.1.1.

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### 11.2.5 Master flat and threshold pixels (bad pixel map) determination: `sinfo_rec_mflat`

- The input flat field frames are stacked. An average with rejection (parameters **lamp\_flats.low\_rejection** and **lamp\_flats.high\_rejection**) is computed to remove dynamic bad pixels (either cosmic rays or transient bad pixels). The mean lamp-off frame is subtracted from the mean lamp-on frame.
- If **lamp\_flats.bad\_ind**==TRUE the intensity tilt of each column is removed (the fit of the pixel intensity is subtracted from the pixel intensity) considering in this operation only pixels whose intensity differs from the linear fit value by no more than **lamp\_flats.sigma\_factor** times the sigma of the pixel intensity.
- To find the strong intensity deviations of bad pixels a threshold value must be found. For this reason, on a rectangular region defined by parameters **lamp\_flats.llx**, **lamp\_flats.lly**, **lamp\_flats.urx**, **lamp\_flats.ury**, the recipe computes a *clean\_mean* of the intensity (**lamp\_flats.bad\_low\_rejection** and **lamp\_flats.bad\_high\_rejection**) and its clean standard deviation *clean\_stdev* (to have an estimate of the noise variations in the flat field). The threshold value is given by the product *clean\_stdev*\***lamp\_flats.factor**.

If **lamp\_flats.thresh\_index**==TRUE the image corrected for the intensity tilt is further filtered, indicating as bad pixels the ones which lie outside the intensity range [*clean\_mean*-**lamp\_flats.mean\_factor**\**clean\_stdev*]. Else no filter is applied. This results in a reference image. A median filter with a radius equal to *clean\_stdev*\***lamp\_flats.factor** is applied for **lamp\_flats.iterations** iterations to remove small clusters of bad pixels. Finally pixels which have different values are promoted to bad pixels by comparing the median filtered image with the reference image.

- A master flat field is determined. If **lamp\_flats.interpol\_ind**==TRUE, using the input bad pixel mask, and the slitlets position information, bad pixels are interpolated over a given radius **lamp\_flats.max\_rad**.

Then the intensity is normalised to that of the central pixel.

For QC purposes the fixed pattern noise is monitored on the resulting master flat field over two rectangular regions defined by parameters **lamp\_flats.qc\_fpn\_xmin1**, **lamp\_flats.qc\_fpn\_xmax1**, **lamp\_flats.qc\_fpn\_ymin1**, **lamp\_flats.qc\_fpn\_ymax1**, and **lamp\_flats.qc\_fpn\_xmin2**, **lamp\_flats.qc\_fpn\_xmax2**, **lamp\_flats.qc\_fpn\_ymin2**, **lamp\_flats.qc\_fpn\_ymax2**, and the recipe computes the number of pixels which lie outside a given range (**lamp\_flats.qc\_thresh\_min** and **lamp\_flats.qc\_thresh\_max**).

A bad pixel mask is then determined on the master flat field by flagging all pixels which deviate too much from a threshold.

The input flat field frames (in our case only the master flat) are stacked. An average with rejection (parameters **bp\_norm.low\_rejection** and **bp\_norm.high\_rejection**) is computed. Pixels whose intensity lie outside the range [**bp\_norm.min\_cut**, **bp\_norm.max\_cut**] are flagged as bad.

- Then the intensity tilt of each column is removed (the fit of the pixel intensity is subtracted from the pixel intensity) considering in this operation only pixels whose intensity differs from the linear fit value by no more than **bp\_norm.sigma\_factor** times the sigma of the pixel intensity.
- The standard deviation and the mean within a defined (**bp\_norm.llx**, **bp\_norm.lly**, **bp\_norm.urx**, **bp\_norm.ury**) rectangular zone is determined in a way that the extreme low (**bp\_norm.low\_cut**) and the extreme high (**bp\_norm.high\_cut**) values are chopped off.

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- A bad pixel map of all the pixels which deviate from a certain threshold level is determined on the master flat field. The input frames are stacked in a cube and an average with rejection (**bp\_norm.low\_rejection**, **bp\_norm.high\_rejection**) is taken to remove cospics. The pixels which lie outside an intensity range set by parameters **bp\_norm.min\_cut** and **bp\_norm.low\_cut** are removed from the resulting median image.
- If **bp\_norm.threshold\_index==TRUE**, pixels deviating more than (**bp\_norm.mean\_factor\*bp\_norm.sigma**) from the clean mean are declared bad. Then a further pixel cleaning is performed involving a pixel's nearest neighbours using one of several methods defined by corresponding values of the parameter **bp\_norm.method\_index** and depending on the values of **bp\_norm.factor** and possibly **bp\_norm.iterations**, as described in [11.1.10](#).
- Then the resulting image is compared with the input image having the column intensity tilt removed and each changed pixel is indicated as bad. Finally, from this final image, a bad pixel mask is produced in which each good pixel is marked with 1 and each bad pixel with 0.

#### 11.2.6 Optical distortion and slitlet distances determination: **sinfo\_rec\_distortions**

- Normal flat frames are combined to determine a master flat and a bad pixel map. To perform this operation some parameters have peculiar default values: **bp\_dist.factor=999.0**, **bp\_dist.mean\_factor=999.0**. These values have been chosen to ensure robustness.
- A set of fibre lamp-on frames are stacked (see [11.2.7](#) recipe for more details) with different rejection thresholds to determine a fake fibres-on and a fake fibres-off frame. Since the distortion coefficients are not yet known, no distortion correction is applied (internally the recipe assumes **stacked.warpfix\_ind == FALSE**). The fake fibres-off frame is subtracted from the fake fibres-on frame.
- Undistorted arc lamp frames are used to determine a wavelength calibration solution.
- The distortion map is computed on the fake fibres-on - fibres-off frame. This step involves the following operations.
  - The stacked fibres-on - fibres-off and ThAr frames are multiplied by the bad pixel map.
  - On the ThAr corrected frame the arc lamp line positions are determined (parameters **distortion.begin\_wave**, **distortion.guess\_disp1**, **distortion.guess\_disp2**, **distortion.min\_diff\_col\_tilt\_int**, **distortion.half\_width**, **distortion.sigma**) as described in [11.1.14](#).
  - A wavelength calibration is performed (the result depends on the following parameters: **distortion.guess\_disp1**, **distortion.half\_width**, **distortion.min\_amplitude**, **distortion.max\_residual**, **distortion.fwhm**, **distortion.n\_a\_coefficients**, **distortion.n\_b\_coefficients**, **distortion.sigma\_factor**, **distortion.pixel\_dist**, **distortion.pixel\_tol**) as described in [11.1.15](#).
  - A possible line shift is computed as described in [11.1.16](#). This result depends also on: **distortion.n\_a\_coefficients**.
  - The slitlet positions are computed as a function of **distortion.box\_length**, **distortion.y\_box**, **distortion.diff\_tol** as described in [11.1.18](#).
  - The slitlet distances are computed with a north-south test as described in [11.1.19](#). In this operation relevant user definable parameters are **north\_south\_test.n\_slits**, **distortion.ns\_half\_width**, **distortion.ns\_fwhm**, **distortion.min\_diff**, **distortion.dev\_tol**, **distortion.lo\_pos**, **distortion.hi\_pos**.



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- Those are averaged to get the position of the first slitlet.
- Finally the distortions are determined (assuming as offset the position found for the first slitlet) as described in [11.1.20](#).
- Finally the fake fibres-on - fibres-off frame is corrected for distortions and the slitlet distances are determined again with a north south test on the frame corrected for distortions.

The north south test involves the following operations:

- The input frames are stacked in a cube and an average with rejection is computed (parameters **north\_south\_test.low\_rejection**, **north\_south\_test.high\_rejection**).
- If **north\_south\_test.gauss\_ind == TRUE** the resulting image is convolved with a Gaussian of FWHM **north\_south\_test.kernel\_half\_width**.
- If **north\_south\_test.mask\_ind == TRUE** the resulting image is multiplied by the input bad pixels map. This image is saved as a product.
- Then the slitlet distances are computed and saved as a table product. The result depends on the following user definable parameters: **north\_south\_test.half\_width**, **north\_south\_test.fwhm** , **north\_south\_test.min\_diff**, **north\_south\_test.dev\_tol**.
- Each of the 32 continuum slit spectra at the same spatial position is fit by a Gaussian along the spatial direction. This determines for each detector's raw the position of each slitlet. Those are averaged along the row. Then the distance of the left edge of each slitlet from a reference one is computed and thus 31 relative distances are found.

### 11.2.7 Wavelength solution determination: **sinfo\_rec\_wavecal**

**Frame stacking** This macro step is common to several recipes: **sinfo\_rec\_distortion**, **sinfo\_rec\_wavecal**, **sinfo\_rec\_jitter**.

- The input arc lamp frames (which can be “on” or “off” frames, or dark calibrations, or objects or sky frames) are stacked.
- The “off” (or sky) frame is subtracted from the “on” (or object) frame.
- If **stacked.flat\_index==TRUE** the result is flat-fielded using the input master flat field.
- Static bad pixels are indicated (**stacked.mask\_ind=1**) or not (**stacked.mask\_ind=0**). If **stacked.mask\_ind=1**:
  - If **stacked.ind\_index** is FALSE bad pixels are interpolated over a given range defined by **stacked.mask\_rad** and using the information on the slitlet edge positions contained in the SLIT\_POS frame.
  - If **stacked.ind\_index** is TRUE bad pixels are indicated by multiplying the frame by the bad pixel map.
- If **stacked.warpx\_ind==TRUE** the distortion is corrected using a given kernel (**stacked.warpx\_kernel**).
- Finally some quality control is performed on the resulting stacked frame by monitoring the number of saturated pixels (**stacked.qc\_thresh\_max**) and the maximum flux.

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**Wavelength calibration** This macro data reduction step determines the dispersion relation and the slitlet position table. If an input slitlet position table is not present one can determine it from scratch by setting the parameter **wavecal.slitpos\_bootstrap\_switch** to TRUE. For the sake of robustness, it is suggested to use **wavecal.slitpos\_bootstrap\_switch** == FALSE and provide an input slitlets positions table, for example the corresponding one (band, preoptics) provided in the calibration data available with this release, and then let the recipe refine it. Reference slitlet position tables are provided together with the SINFONI pipeline.

- The input arc lamp-on and lamp-off frames are loaded.
- If **wavecal.calib\_indicator** == TRUE and **wavecal.wave\_map\_ind** == TRUE the input arc lamp reference line list is loaded.
- If one needs to do the wavelength calibration (**wavecal.calib\_indicator** == TRUE and **wavecal.wave\_map\_ind** == FALSE), the recipe finds the emission lines present in each arc lamp spectrum as described in [11.1.14](#)
- Then the dispersion relation is determined as described in [11.1.15](#).
- The overall line shift between the solution found from the fit as described in [11.1.16](#) and the position of the lines in the frame is monitored for quality control.
- Then the recipe logs additional QC parameters: the number of found lines, the number of saturated pixels, the flux maximum of the frame difference “on” - “off”.
- The wavelength map is saved. This is an image in which each pixel is associated with a wavelength value in microns.
- If **wavecal.write\_coeff\_ind**==TRUE the polynomial fit coefficients are saved in a FITS table.
- If **wavecal.write\_par\_ind**==TRUE the Gaussian fit parameters are saved in a table. The number of detected lines, the median and the average FWHM are monitored for quality control.
- If a wavelength map is available (**wavecal.wave\_map\_ind**==TRUE) and a dispersion relation does not need to be found (**wavecal.calib\_ind**==0) one may want to correct what is already available to match the actual arc lamp frame, by creating a shifted dispersion relation. Then the overall line shift between the solution found from the fit and the position of the lines in the frame is computed.
- Finally if **wavecal.calib\_indicator**==TRUE and **wavecal.estimate\_indicator**==TRUE the slitlet positions are fit using a parameter list input FITS table. The slitlet position determination may follow either the Boltzmann or the estimate methods as described in [11.1.18](#).

In the end the recipe generates also a resamples the arc lamp stacked frame to control the quality of the performed wavelength calibration.

### 11.2.8 Science observations: **sinfo\_rec\_jitter**

- The input frames are selected defining obj-sky pairs. In case a sky frame is missing in the set of frames a sky frame is estimated as described in [11.1.25](#). Each pair is stacked.

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- Each stacked frame is resampled using the information from the input calibration image (WAVE\_MAP) doing a polynomial interpolation with **objnod.n\_coeffs** parameters to generate an output 3D frame as described in 11.1.21. This operation determines the dispersion, the minimum, the maximum and the central wavelength as well as the central pixel of the output calibrated image.
- If **objnod.north\_south\_ind** == FALSE, a 3D frame is reconstructed from each stacked frame by using the information contained in the slitlet position table SLIT\_POS.
- If the user provides in input a reference atmospheric refraction correction catalog frame (part of this kit distribution) tagged as ATM\_REF\_CORR, the recipes applies the atmospheric correction. This correction is important in particular in 25 mas setting where otherwise, after cube reconstruction, the object PSF center may move up to several spaxels (see 11.1.30).
- The 3D frame is refined using different methods (**objnod.fine\_tuning\_method**). Possible values are P (polynomial of order **objnod.order**), S (Spline). The 3D frame is stretched in Y to make it appear as a parallelepipedus with a square cross-section. We usually call this a “3D cube”.
- If **objnod-sky\_cor** is TRUE and if the recipe parameter **product-density** is set to 3 sky line residuals are corrected as described in 11.1.26. We suggest to use this setting only after having verified that otherwise the object spectrum contains sky line residuals. A more personalized correction of sky line residuals would follow the following steps: reduce the data without correcting for residuals and setting **product-density** to 2. Then correct each corresponding obj-sky pair with **sinfo\_utl\_skycor** and proper parameter setting. Finally use **sinfo\_utl\_cubes\_combine** to reconstruct a cube mosaic.
- If **objnod.jitter\_index**==TRUE, finally all the cubes corresponding to the different object jittered positions are merged into a big data cube by averaging the overlap regions weighted by integration times and using a given kernel type **objnod.kernel\_type** as described in 11.1.22 possibly scaling the sky background (if **objnod.scale\_sky** == TRUE) and doing a kappa sigma clipping (if **objnod.kappa\_sigma** == TRUE) of intensity outliers.

### 11.2.9 STD star data reduction: sinfo\_rec\_jitter

The initial data reduction is the same as the one of a normal science frame (sinfo\_rec\_jitter). Then if the input object is a PSF or flux standard star:

- The position of the source maximum, its centroid and FWHM, are determined from the average image of the coadded cube. Those parameters are used to automatically set the optimal extraction parameters in a square region whose size depends on the average of the FWHM in the X and Y directions and a user definable scale parameter **std\_star.factor**, eventually reduced in case the star position falls outside the actual z-cross section plane. The output is in the form of an image and a table. If **std\_star.conversion\_index**==TRUE a conversion magnitude to counts/seconds is performed. The intensity conversion factor (magnitude per count/s) is determined by fitting 2D Gaussian to the collapsed image of the observed standard star of known brightness. Then the fresulting Gaussian is integrated and the counts are divided by the exposure time.

The integration is made on a rectangular box of a given size (half box size is 16 pixels), centered at a given position (llx=llly=8). In case of more than an input standard star, it is computed a clean mean of the clean factors obtained by each standard star.



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- The instrument efficiency is determined as described in [11.1.27](#).
- The extracted star spectrum and the efficiency are saved in a table.

#### **11.2.10 PSF data reduction: sinfo\_rec\_jitter**

The initial data reduction is the same as the one of a normal science frame. Then if the input object is a PSF or flux standard star, the main PSF standard parameters, the instrument Strehl and the encircled energy are determined as described in [11.1.28](#) and [11.1.31](#).

#### **11.2.11 PUPIL data reduction: sinfo\_rec\_pupil**

The initial data reduction is the same as the one of a normal science frame. Then the X and Y centroid of the cube's median image are determined.

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## A Installation

This chapter gives generic instructions on how to obtain, build and install the SINFONI pipeline. Even if this chapter is kept as up-to-date as much as possible, it may not be fully applicable to a particular release. This might especially happen for patch releases. One is therefore advised to read the installation instructions delivered with the SINFONI pipeline distribution kit. These release-specific instructions can be found in the file `README` located in the top-level directory of the unpacked SINFONI pipeline source tree. The supported platforms are listed in Section A.1. It is recommended reading through Section A.2.2 before starting the installation.

A bundled version of the SINFONI pipeline with all the required tools and an installer script is available from [www.eso.org/pipelines](http://www.eso.org/pipelines), for users who are not familiar with the installation of software packages.

### A.1 Supported platforms

The utilisation of the GNU build tools should allow to build and install the SINFONI pipeline on a variety of UNIX platforms, but it has only been verified on the VLT target platforms:

- Linux (glibc 2.1 or later),
- Mac,

using the GNU C compiler (version 3.2 or newer). Gasgano is installed by the `install_pipeline` script and is supported provided the user has a proper installation of the Java Development Kit (version 1.6.0 or newer) and has set the `JAVA_HOME` environment variable properly during the kit installation. It is not sufficient to have the Java Realtime Environment to have successfully installed the `libgasganocpl.*` libraries needed to properly interface Gasgano with the installed `sinfoni` recipes. We recommend the user to look carefully at the log produced during installation and possible warnings.

### A.2 Building the SINFONI pipeline

This section shows how to obtain, build and install the SINFONI pipeline from the official source distribution.

#### A.2.1 Requirements

To compile and install the SINFONI pipeline one needs:

- the GNU C compiler (version 3.2 or later),
- the GNU `gzip` data compression program,
- a version of the `tar` file-archiving program, and,
- the GNU `make` utility.

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An installation of the Common Pipeline library (CPL) must also be available on the system. Currently the CPL version 5.3.1 or newer is required. The CPL distribution can be obtained from [www.eso.org/cpl](http://www.eso.org/cpl).

In order to run the SINFONI pipeline recipes a front-end application is also required. Currently there are two such applications available, a command-line tool called *EsoRex* and the Java based data file organizer, *Gasgano*, which provides an intuitive graphical user interface (see Section 5.2, page 20). At least one of them must be installed. The *EsoRex* and *Gasgano* packages are available at [www.eso.org/cpl](http://www.eso.org/cpl) and [www.eso.org/gasgano](http://www.eso.org/gasgano) respectively.

For installation instructions of any of the additional packages mentioned before please refer to the documentation of these packages.

## A.2.2 Compiling and installing the SINFONI pipeline

The SINFONI pipeline distribution kit 2.2.5 contains:

sinfo-pipeline-manual-15.0.pdf	The SINFONI pipeline manual
install_pipeline	Install script
cfitsio3090.tar.gz	CFITSIO 3.09.0
cpl-5.3.1.tar.gz	CPL 5.3.1
esorex-3.9.1.tar.gz	esorex 3.9.1
gasgano-2.4.0.tar.gz	GASGANO 2.4.0
sinfoni-2.2.5.tar.gz	SINFONI 2.2.5
sinfoni-calib-2.2.5.tar.gz	SINFONI calibration files 2.2.5

Here is a description of the installation procedure:

1. Change directory to where you want to retrieve the SINFONI pipeline recipes 2.2.5 package. It can be any directory of your choice but not:

```
$HOME/gasgano
$HOME/.esorex
```

2. Download from the ESO ftp server, [www.eso.org/pipelines](http://www.eso.org/pipelines), the latest release of the SINFONI pipeline distribution.
3. Verify the checksum value of the tar file with the cksum command.
4. Unpack using the following command:  
**tar -xvf sinfo-kit-2.2.5.tar**

Note that the size of the installed software (including *Gasgano*) together with the static calibration data is about 27Mb.

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5. Install: after moving to the top installation directory,

**cd sinfo-kit-2.2.5**

it is possible to perform a simple installation using the available installer script (*recommended*):

**./install\_pipeline**

(beware: the execution may take a few minutes on Linux and several minutes on SunOS).

By default the script will install the SINFONI recipes, *Gasgano*, *EsoRex*, all the necessary libraries, and the static calibration tables, into a directory tree rooted at `$HOME`. A different path may be specified as soon as the script is run.

The only exception to all this is the *Gasgano* tool, that will always be installed under the directory `$HOME/gasgano`. Note that the installer will move an existing `$HOME/gasgano` directory to `$HOME/gasgano.old` before the new *Gasgano* version is installed.

Important: the installation script would ensure that any existing *Gasgano* and *EsoRex* setup would be inherited into the newly installed configuration files (avoiding in this way any conflict with other installed instrument pipelines).

Alternatively, it is possible to perform a manual installation (*experienced users only*): the `README` file located in the top installation directory contains more detailed information about a step-by-step installation.

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## B Abbreviations and acronyms

ANSI	American National Standards Institute
ASCII	American Standard Code for Information Interchange
CalibDB	Calibration Database
CPL	Common Pipeline Library
DPD	Data Products Department
DFS	Data Flow System department
DMD	Data Management and Operations Division
DRS	Data Reduction System
ESO	European Southern Observatory
ESOREX	ESO-Recipe Execution tool
FITS	Flexible Image Transport System
FOV	Field Of View
FPN	Fixed Patter Noise
GUI	Graphical User Interface
OB	Observation Block
PSD	Pipeline Systems Department
PSO	Paranal Science Operations
QC	Quality Control
RON	Read Out Noise
SDD	Software Development Division
SINFONI	Spectrograph for INtegral Field Observations in the Near Infrared
SOF	Set Of Frames
SPIFFI	SPectrograph for Infrared Faint Field Imaging
UT	Unit Telescope
VLT	Very Large Telescope

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