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VERY LARGE TELESCOPE

NIRPS Pipeline User Manual

NIRPS-4500-GEN-UM-211

Issue 2.4.16

Date 2021-05-15

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1 Introduction

1.1 Purpose

The ESPRESSO pipeline adapted for NIRPS is a subsystem of the *VLT Data Flow System* (DFS). Through the rest of the document it will be called NIRPS pipeline. Its target user is both the user community and ESO *Data Products Department* (DPD) in the generation of master calibration data, in the reduction of scientific exposures, and in the data quality control. Additionally, the NIRPS pipeline recipes are made public to the user community, to allow a more personalised processing of the data from the instrument. The NIRPS pipeline was developed with the declared objective of providing precise Radial Velocity (RV) data and accurate wavelength calibration. The purpose of this document is to describe a typical NIRPS data reduction sequence with the NIRPS pipeline.

This manual is a complete description of the data reduction recipes implemented by the the NIRPS pipeline, reflecting the status of the NIRPS pipeline as of May 15, 2021 (version 2.4.16).

1.2 Acknowledgments

The NIRPS pipeline has been designed, implemented and developed by the Geneva Observatory. We are particularly grateful to the responsables for the data reduction: Christophe Lovis, Danuta Sosnowska and Alex Segovia for their contributions and support.

Andrea Modigliani, from ESO, provided DFS support and most of the documentation.

1.3 Scope

This document describes the NIRPS pipeline used at ESO-Garching and ESO-La Silla 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]. A description of the instrument is in [6]. The NIRPS instrument user manual is in [7].

1.4 Reference documents

- [1] NIRPS Pipeline Users' Manual NIRPS-4500-GEN-DER-211
www.eso.org/pipelines
- [2] Current pipeline status
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
- [5] ESOREX home page www.eso.org/cpl/esorex.html
- [6] NIRPS home page

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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 three main purposes:

Data quality control: pipelines are used to produce the quantitative information necessary to monitor instrument performance.

Master calibration product creation: pipelines are used to produce master calibration products (*e.g.*, combined dark frames, super-flats).

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 in La Silla or from Gasgano.

ESO offers two front-end applications for launching pipeline recipes, *Gasgano* and *EsoRex* [5] both included in the pipeline distribution (see Appendix A, page 63). These applications can also be downloaded separately from www.eso.org/gasgano and www.eso.org/cpl/esorex.html. GASGANO is a Data File Organiser developed and maintained by ESO to help its user community to manage and organise in a systematic way the astronomical data observed and produced by all VLT compliant telescopes, *i.e.* by telescopes which are being operated through Observation Blocks. The tool also supports FITS files which are not generated by those telescopes with limited functionality. For further information, please, refer to the latest [Gasgano User's Manual](#). In the special case of the NIRPS pipeline, which uses a lot of RAM, we decided not to provide Gasgano support.

As mentioned in the introduction, the NIRPS pipeline is based on the ESPRESSO pipeline. Most of its functionalities and the way of using it are the same as in the ESPRESSO pipeline. However, there are some differences, mainly due to the fact, that NIRPS is a near-infrared spectrograph, while ESPRESSO works in the visible wavelengths. Here are the differences:

- There are two instrument modes: High Accuracy (HA) and High Efficiency (HE), both with binnings 1x1
- There are no modes with slices of orders, all the orders are mono-slice
- Due to the water vapor absorption around the wavelength of 1.4 micron, the order with the echelle number 105 is dropped on the spectra
- Images are preprocessed to remove the offsets of the amplifiers, the residual 1/f noise and the NaNs
- No mbias recipe: the infrared detectors have the bias subtracted while preparing the final raw frame, so also no overscan subtraction through the reduction chain

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- Dark current subtraction is done through the scaled MASTER_DARK frame and not with the mean dark current scaled value
- For the wavelength solution a Uranium-Neon lamp is used instead of the Thorium-Argon, but all the tables/catalogues formats stay the same

Recent pipeline improvements are listed in [Section 3](#). The NIRPS instrument is described in [Section 4](#). In [section 5](#) we list known data reduction problems for the NIRPS pipeline and possible solutions. The different types of NIRPS raw frames and auxilliary data are described in [Sections 6](#), and [7](#). An overview of the data reduction, the input data, and the recipes involved in the calibration cascade is provided in [section 8](#). More details on inputs, products, quality control measured quantities, and controlling parameters of each recipe is given in [section 9](#). A brief introduction to the usage of the available reduction recipes using EsoRex is presented in [Section 10.2](#). 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 NIRPS pipeline recipes is described.

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3 Recent improvements

This release of the NIRPS pipeline (version 2.4.16) includes the following major improvements with respect to previous public release:

- Full functionality of all recipes tested with the NIRPS commissioning data

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4 NIRPS Instrument Description

NIRPS is the Near Infra-Red echelle spectrograph for Planet Search installed at the 3.6 telescope in the La Silla observatory. It is an ultra-stable fibre-fed échelle high-resolution spectrograph working in parallel together with his twin in the visible wavelengths - HARPS.

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

4.1 Instrument overview

NIRPS was built by the NIRPS consortium consisting of Université de Montréal (UdM), Université de Genève (UniGe), Instituto de Astrofísica de Canarias (IAC), Université Grenoble Alpes (UGA), Instituto de astrofísica e ciencias do espaço (IA), Universidade Federal do Rio Grande do Norte (UFRN) and with substantial contribution from ESO-LaSilla and ESO-Garching. The design of NIRPS is based on experience acquired with HARPS, ESPRESSO and SPIROU. NIRPS is a fiber-fed, cross-dispersed echelle spectrograph operating in the near-infrared in a cryogenic vacuum tank located in the Coud'e floor of the 3.6m telescope. NIRPS is an adaptive optics (AO) fiber-fed spectrograph. The AO system leads to an efficient coupling into a 0.4-arcsecond multi-mode fiber. A 0.9-arcsecond fibre is used for fainter targets and degraded seeing conditions. NIRPS is composed of four different subsystems: the Front-End, the Calibration Unit, the fiber link, the spectrograph and the detector. These are represented on the next figure and described in the following sections.

4.2 The Front End

The Front-End (FE) sub-system is composed of TBC The AO system is designed around a 14×14 Shack-Hartmann wavefront sensor (WFS) operating between 700 and 950 nanometres, coupled to a 15×15 deformable mirror with a loop frequency of 250 to 1000 Hz.

4.3 The Spectrograph

The cryogenic enclosure is maintained at 80 K within 1 mK RMS and a pressure $< 10^{-7}$ mbar. No moving parts are located inside the cryogenic enclosure. All necessary moving parts are located in the NIRPS Front-End (or NIRPS Cassegrain Fiber Adapter).

4.4 Fiber Link

4.5 Calibration Unit

The calibration system is a separate unit that contains light sources: tungsten lamp, Fabry-Perrot, Uranium-Neon lamp and the laser frequency comb, controllers and injection optics. The laser frequency comb is not yet available. The light is transmitted via optical fibres. This unit has its own control module for the various lamps and lasers power supplies. The whole calibration unit is fitted into a standard rack and is composed of the following elements:

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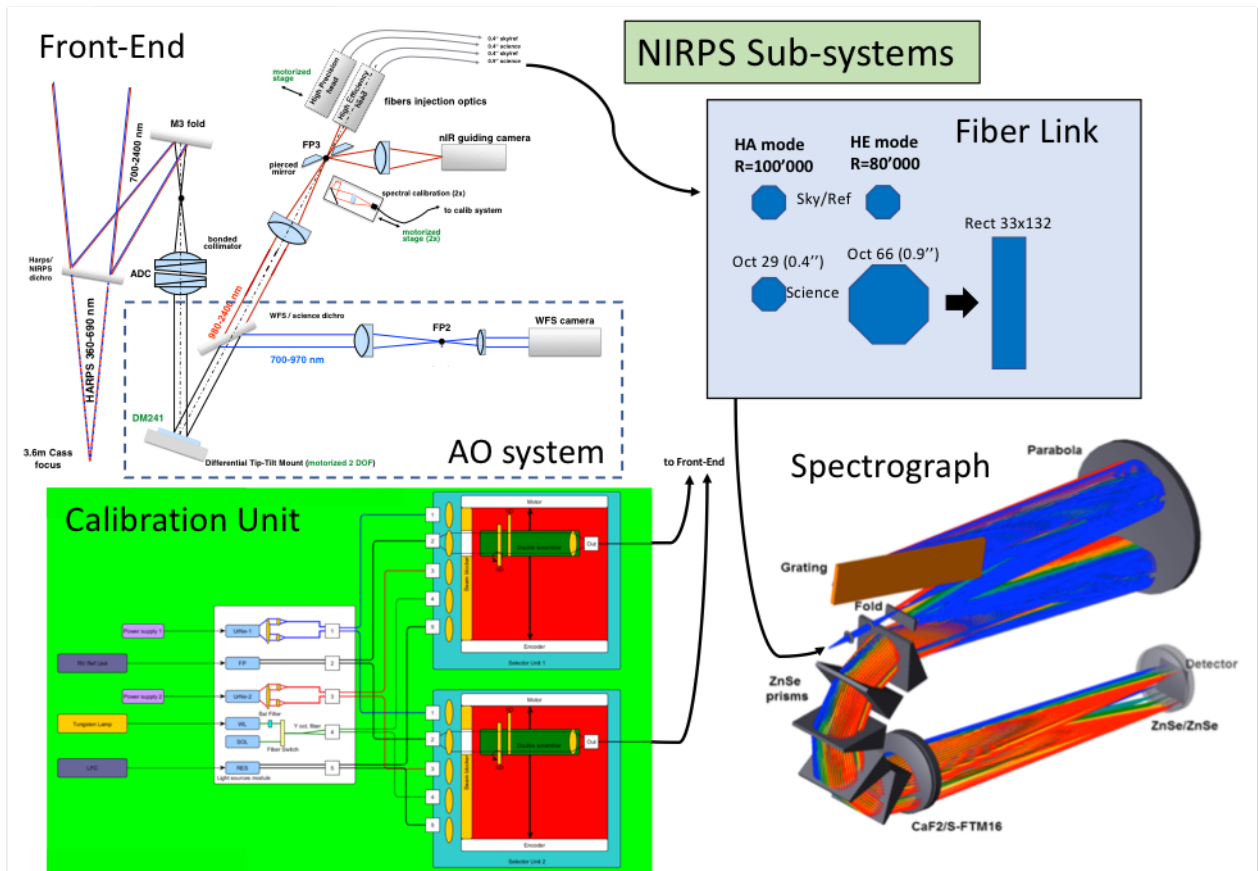


Figure 4.1: NIRPS and its different subsystems: Front-End, Calibration Unit, Fiber Link and Spectrograph

- 2 identical modules named selector unit 1 and 2 (SU1, SU2)
 - 6 lenses
 - 1 linear stage for input selection (LS_in)
 - 1 rotary stage for continuous neutral density filters
 - Lens and fibre mounts fully adjustable for in and output injection o 1 beam blocker
- Lamps
 - 2 fibre-coupled laser diodes at 642 nm and 1064 nm
 - 1 single mode fibre coupled laser diode at 642 nm
 - 2 Uranium-Neon lamps with two fibre outputs each (octagonal, 320 microns and NA 0.125)
 - 1 Tungsten lamp with two fibre outputs each (octagonal, 320 microns and NA 0.125)
- Electronics

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- 1 module containing control electronics
- Fiber connections
 - Input fibres to selector units shall be octagonal fused silica fibres having a diameter of 320 microns and NA 0.2 with FC connector and bending protection.
 - Output fibres from selector units shall be octagonal fused silica fibres having a diameter of 320 microns and NA 0.2 with FC connector and bending protection.
 - FP1 and FP2 are single mode fibres with diameter of 5.3 microns and NA 0.14 with FC connector and bending protection.
- Rack
 - Standard cabinet with airflow and water cooling system

The LFC and FPCS sources are considered external form calibration unit and shall deliver octagonal fused silica fibres having a diameter of 320 microns and NA 0.2 with FC connector and bending protection.

4.6 Detector

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5 Known problems

Several pipeline problems have been identified:

- **Failure of THAR-FP or FP-THAR reduction** The reduction of THAR-FP or FP-THAR fails sometime, when the `espdr_wave_FP` recipe does not detect FP peaks on the whole order. This can be due to a strong cosmic, badly placed. The consequence is the impossibility to construct the wavelength solution. In this case it is possible to take another FP-FP raw frame for the reduction.
- **wave_FP fails** Occasionally WAVE,FP,FP frames may have cosmics that may induce a recipe failure. For example we encounter this problem and the reported error was like the following:

```
[ INFO ] espdr_wave_FP: Checking FP peaks for fibre A
[WARNING] espdr_wave_FP: Delta x bigger for order 92 pxl 297.402747, delta =
[WARNING] espdr_wave_FP: Peak_pxls: 291.580109, 297.402747, 309.016369
[ ERROR ] espdr_wave_FP: Missing peaks in the FP image, aborting.
[ ERROR ] espdr_wave_FP: Dumping all 1 error(s):
[ ERROR ] espdr_wave_FP: [1/1] 'Input data do not match' (13) at espdr_wave
[ ERROR ] esorex: Execution of recipe 'espdr_wave_FP' failed, status = 13
[ INFO ] esorex: Calculating product checksums
[WARNING] esorex: Writing of output sof omitted due to previous errors
```

Already the warning indicates something suspicious happen. Often the source of the problem is one or more cosmic on the frame. Often this problem can be solved during extraction simply by reducing the parameter `fp_extraction_ksigma` from the default 5 to a smaller value.

For updated information we recommend the user to also read the Data Reduction F.A.Q. page: <http://www.eso.org/sci/data-processing/faq.html>.

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6 Instrument Data Description

The NIRPS instrument produces raw data in two different configurations or modes: High Accuracy (HA) and High Efficiency (HE). Those are defined by the instrument mode KW: HIERARCH ESO INS MODE.

The NIRPS pipeline considers these two modes as independent instruments for the purpose of data reduction. This means that, to be processed by the pipeline a science frame in a given mode requires a complete calibration dataset in the same mode. As part of the NIRPS operational scheme at the observatory, the acquisition of the calibrations in both modes is done before every night of observations.

To reduce a science frame, the following raw calibration frames are needed:

type	# frames	comments
DARK	5	long exposure time (>20min), to determine hot pixels
LED	2x5	2 different exposure times, to determine non linear pixels and conversion factor
ORDERDEF	2	each frame illuminates only one fiber, to trace orders
FLAT	2x10	2 sets, illuminating fib A and B, to determine short and long scale responsiveness variations
FP-FP	1	both fibres illuminated by Fabry Perot etalon, for wavelength calibration
UN-FP	1	fib A illuminated by ThAr, fibre B by FP, for wavelength calibration
FP-UN	1	fib B illuminated by ThAr, fibre A by FP, for wavelength calibration
SKY,SKY	1	both fibres observing zenith sky, to determine relative fibre efficiency
STD,SKY	1	fib A observes a spectrophotometric standard, fib B observes the sky to flux calibrate the observed science spectrum

Optionally, the following calibration frames are needed for wavelength calibration with the laser frequency comb (LFC):

type	# frames	comments
LFC-FP	1	for wavelength calibration, optional
FP-LFC	1	for wavelength calibration, optional

Optionally, the following calibration frame is needed to correct for cross-fiber contamination by the FP in simultaneous-reference mode:

type	# frames	comments
DARK-FP	1	frame to determine contamination of fib B on A

It is also necessary to have a set of static calibration data (see next Section).

The following sections provides a brief description of each raw data type involved in the data reduction chain.

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6.1 DARK frames

Dark frames are taken to measure the detector dark current and identify hot pixels. A set of five input frames is acquired, each with 60 reads.

6.2 Detector Flat-field (LED) frames

Detector flat-field frames are images taken while illuminating the detector with a uniform LED light. At least two sets, each composed by at least five frames, with different number of reads are required.

6.3 ORDERDEF frames

Two frames are acquired: ORDERDEF_A and ORDERDEF_B and used for order/slice definition, identification and tracing for fibre A and B. A continuum light source is used to illuminate fibre A (or B), while fibre B (or A) is dark (separate frames for different fibres are necessary for the automatic identification of orders or slices). In order to recover as much as possible of the orders in the gap of 1.4 micron. It is normal to have these frames very saturated.

6.4 FLAT frames

Two set of frames are acquired: FLAT_A and FLAT_B and used to derive the order profile in cross-dispersion direction, the spectral flat-field, and the blaze function of the spectrograph for fibres A and B. A continuum light source is used to illuminate fibre A (or fibre B), while fibre B (or fibre A) is dark. Several exposures (at least 10) are required to reach sufficiently high SNR.

6.5 Wavelength calibration frames

Three sets of frames are acquired to perform the wavelength calibration. These are acquired with different calibration sources and combined together to cross-calibrate the wavelength references of the two fibres.

- FP_FP: This frame is obtained illuminating both fibres with a Fabry Perot.
- UN_FP: This frame is obtained illuminating fibre A with a UNE lamp and fibre B with a Fabry Perot.
- FP_UN: This frame is obtained illuminating fibre B with a UNE lamp and fibre A with a Fabry Perot.
- LFC_FP (optional): This frame is obtained illuminating fibre A with a laser comb and fibre A with a Fabry Perot.
- FP_LFC (optional): This frame is obtained illuminating fibre B with a laser comb and fibre A with a Fabry Perot.

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6.6 Contamination by simultaneous reference frames

- **CONTAM_FP**: Measurement of contamination light induced on fibre A by FP simultaneous reference on fibre B. Fibre A is dark, while FP light is injected into fibre B as in a science exposure with simultaneous reference (i.e. same flux level).

6.7 Fiber-to-fiber Relative Efficiency frames

EFF_AB: Relative efficiency of fibre B vs. fibre A as a function of wavelength. During twilight, the telescope is pointed at zenith and the skylight is injected into both fibres.

6.8 Spectrophotometric Calibration (FLUX) frames

FLUX_CALIB: A spectrophotometric standard star is observed, as in a science exposure, with sky.

6.9 SCIENCE frames

The following frames are acquired:

- **SCIENCE_FP**: Science exposure (target on fibre A) with Fabry-Perot simultaneous reference on fibre B.
- **SCIENCE_SKY**: Science exposure (target on fibre A) with simultaneous sky on fibre B.

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7 Static Calibration Data

In the following section static calibration (called also ancillary) data required for NIRPS data reduction are listed. Static calibration data correspond to Images or Tables describing configuration setups, reference data, or characteristics of the instrument that are considered to be fixed. This sets them apart from the calibration previously described. For each of them we indicate the corresponding value of the HIERARCH ESO PRO CATG, in short its PRO.CATG, which has to be used to identify the frames listed in the *Set of Frames*.

7.1 CCD Geometry Table

These are the static CCD configuration tables describing the CCD geometry. The table contains the number and sizes of the detectors, outputs and prescan and overscan regions. Its PRO.CATG is CCD_GEOM.

7.2 Instrument Configuration Table

These are the static instrument configuration tables providing the pipeline recipes with all necessary input parameters that are intimately linked to the instrument configuration being used. There will be one such table per instrument mode (i.e. HA and HE). In case of substantial changes in the instrument optics or HW, that influence the spectral format, new instrument configurations might be created and then used with timestamps. Its PRO.CATG is INST_CONFIG.

7.3 Orders masks

These static frames are masks, that show which pixels belong to the orders and which ones to the background. Needed during the preprocessing phase. Their PRO.CATG is ORDER_MASK_A/B.

7.4 Led Flat Field gain windows Table

These static tables indicate for each detector and detector read-out region the windows where the conversion factor is computed. Their PRO.CATG is LED_FF_GAIN_WINDOWS.

7.5 Wavelength Matrix Images

These are the wavelength calibration arrays (one per fibre) in S2D format, with the wavelength of each extracted pixel stored as data value. These are used as static input frames in the flat and wavelength (THAR/FP or FP/THAR) data reduction. Their PRO.CATG is STATIC_WAVE_MATRIX_A/B¹.

¹As static WAVE and DLL matrix frames, have a large size, to reduce the size of the pipeline package, we decided to include them in the demo data, available <http://www.eso.org/sci/software/pipelines/>, and to deliver them to the user together with the raw data when retrieved with the calSelector tool. The FITS filename of the frame delivered with the demo data contains the instrument mode, the binning, the corresponding PRO.CATG and fibre information and a date that correspond to the date since the frame is valid. Raw data should be associated with the closest in time static frame.

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7.6 DLL Matrix Images

These are the pixel widths in wavelength calibration arrays (one per fibre) in S2D format, with the width in wavelength of each extracted pixel stored as data value. These are used as static input frames in the wavelength (THAR/FP or FP/THAR) and science data reduction. Their PRO.CATG is `STATIC_DLL_MATRIX_A/B`².

7.7 Uranium-Neon emission lines tables

These are the static Uranium-Neon emission lines - UNe - tables (one per fibre) containing the wavelengths, approximate positions, flux and values of D - the FP mirrors distance, for the emission lines found in the UNe extracted spectra (S2D). The column called "grouping" is used to save the mode of the corresponding FP peak. Their PRO.CATG is `REF_LINE_TABLE_A/B`.

7.8 Flux Standard Star tables

The Flux Standard Star Table lists all the stars (part of the calibration plan) for which we have a precise physical flux calibration [$\text{ergs/s/cm}^2/\text{\AA}$] on an even wavelength scale. The table contains absolute spectral energy distributions of a sample of spectrophotometric standard stars. It is a required input of the recipe `espdr_cal_flux` during response and efficiency estimation, where the observed photometric standard star spectrum, after proper rescaling by exposure time, gain and atmospheric extinction, is divided by the spectrum of the corresponding standard star from this catalog. Its PRO.CATG is `STD_TABLE`.

7.9 Extinction Table

This is the table containing the atmospheric extinction curve for Paranal, as provided in Patat et al. (2011), A&A 527, 91 (their Appendix B). This is used in the `espdr_cal_flux` to determine the efficiency and instrument response and in the `espdr_sci_red`, toflux calibrate the observed science object spectrum. Its PRO.CATG is `EXT_TABLE`.

7.10 Flux Template Table

This is the table containing observed spectral energy distributions of a sample of reference stars with different spectral types spanning late-F to early-M. Suitable stars are solar-metallicity dwarf stars of spectral types F to M, observed at high SNR and at low airmass. To build the flux template, the S2D flux of the star is summed in each spectral order and normalised to one at an arbitrary wavelength (e.g. 550nm). The flux template is simply the integrated normalised flux in each spectral order. Flux Template table corresponds to the flux distribution as a function of wavelength for stars of different spectral types. This primordial flux is used to correct the effect of chromatic extinction of the atmosphere, composed of several factors, like Rayleigh scattering and ozone + aerosols absorption. Its PRO.CATG is `FLUX_TEMPLATE`.

²DLL stands for Delta LL, a short notation corresponding to Delta Wavelength.

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7.11 CCF Template Tables

The template tables, or CCF masks, are used by the cross-correlation process. They consist of a list of rest (RV=0) wavelengths for the spectral lines of interest, along with their relative depth (contrast) with respect to the continuum. Depths are used as weights in the CCF process since Doppler precision is proportional to line depth. Their PRO.CATG are MASK_TABLE.

These CCF masks are created from actual NIRPS tellurics free spectra of stars covering a range of sub-spectral types. Spectral lines are identified through an automatic procedure and included in the mask if they meet a number of criteria such as large enough depth and limited blending. The current pipeline version includes CCF masks for G2, K5 and M2 spectral types (individual fits files). The masks cover the full wavelength range of NIRPS.

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8 Data Reduction

We give below an overview of the global reduction cascade, starting from basic calibrations down to science reduction. The NIRPS association map is shown in Figure 8.1.

- DARK frames are used to measure the average detector dark current and identify the hot pixels. The master dark frame is generated via stacking and sigma-clipping to remove the cosmics. The mean dark current level per output and the hot pixels are computed on the master dark frame and stored in the hot pixel mask. The hot pixels are obtained through the sigma-clipping applied on the master image of each detector output.
- Detector flat-field frames are acquired to characterise unresponsive (“dead”) pixels or pixels with a very different gain (so called: bad pixels). For each exposure time, a set of minimum five LED_FF frames is needed to remove the cosmics via the sigma clipping on the pixel-by-pixel basis. The bad pixel mask is obtained from the analysis of master LED_FF frames taken with different exposure times (linearity check). The conversion factor is measured for each detector output from the relation between flux level and standard deviation of pixel values. It is stored in the bad pixel mask.
- ORDERDEF frames (one per fibre) are used to identify and trace spectral orders or slices on the detector. Each order or slice is fitted in the cross-dispersion direction, with a gaussian every defined number of pixels. The gaussian peaks are fitted with a low degree polynomial, of which coefficients are saved in the recipe products.
- For each fibre, the order profile in cross-dispersion direction is found using high-SNR, co-added FLAT frames. Then, the orders are extracted from the FLAT frames using this profile, and the spectral flat-field is generated. The (extracted) blaze function is obtained through smoothing of the FLAT spectra and correction for the spectral energy distribution of the calibration lamp. The order extraction assumes that 1) main-dispersion direction runs approximately parallel to detector rows/columns, and 2) slit image tilt is close to zero with respect to detector columns/rows. In this case, order extraction becomes extremely simple and does not require wavelength calibration frames to track different positions along the slit. The NIRPS optical design makes this strategy possible (line tilt very close to zero), and even recommended owing to its simplicity. This method has been successfully applied to HARPS, ESPRESSO and other radial-velocity spectrographs.
- CONTAM frames are used to measure cross-fibre contamination on fibre A from the simultaneous reference on fibre B (ThAr lamp, laser comb or Fabry-Perot). Contamination frames can be used during extraction in the science reduction.
- The relative efficiency of channels A and B as a function of wavelength is measured using EFF_AB frames, which are obtained through blue sky observations. The obtained relative efficiency is used to scale the subtraction on science exposures with simultaneous sky.
- The wavelength calibration for both fibres is determined using WAVE frames. It is done in two steps: first with the Fabry-Perot on both fibres and then with one of the fibres illuminated by UNE lamp. In the future an additional wavelength solution could be computed using frames with Laser Frequency Comb. On fibre A (science fibre), the wavelength solution is particularly important since it is used to calibrate the science spectrum and therefore sets the radial velocity zero point. On fibre B, the simultaneously acquired

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spectrum mainly serves as reference to calculate the drift on science frames that use FP as simultaneous reference.

- FLUX_CALIB frames are used to compute the absolute efficiency of the instrument as a function of wavelength, using spectrophotometric standard stars. The efficiency is computed from the comparison between the observed spectrum and reference flux table. The efficiency curve is used in the science reduction to calibrate the science spectrum in flux. The precision of the flux calibration is generally low because of highly variable fibre losses due to seeing.
- Finally, SCIENCE frames are of two different sub-types depending on the source of light on the fibre B: sky or Fabry-Perot. Science reduction makes use of all calibration products listed above and generates extracted S2D spectra and merged, rebinned S1D spectra, together with S2D and S1D error and quality maps. Finally, the cross-correlation function (CCF) of the S2D spectrum is computed and the radial velocity is obtained from a Gaussian fit to the CCF.

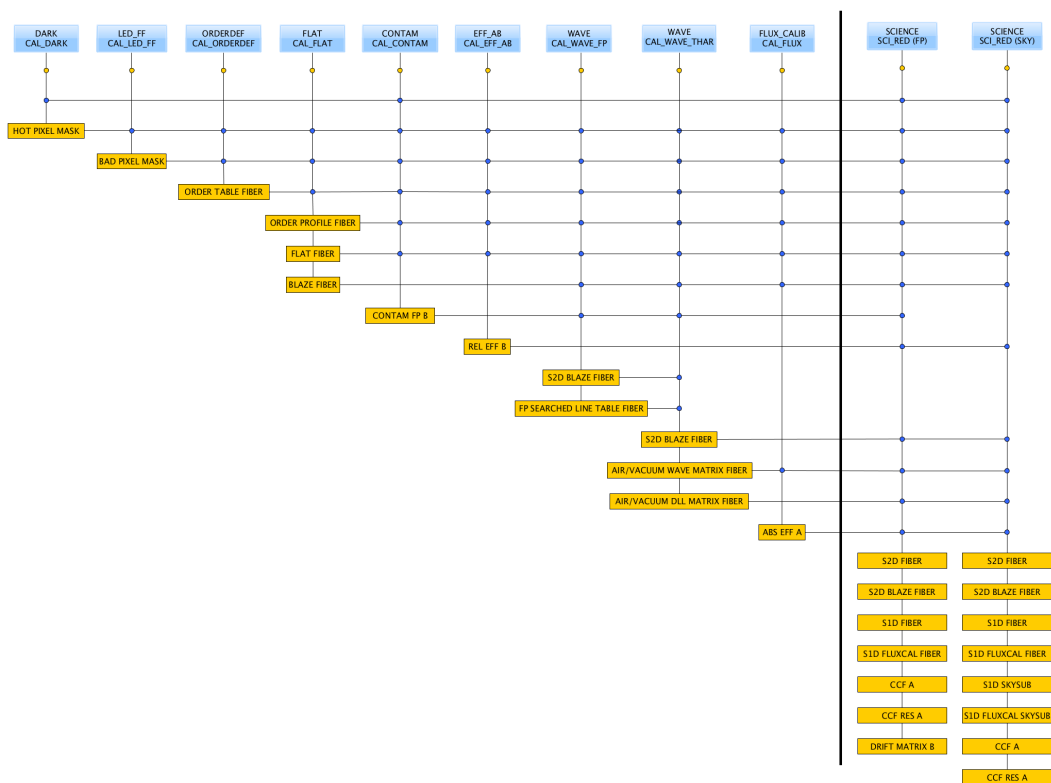


Figure 8.1: The cascade of the NIRPS pipeline recipes. For the calibration recipes, only the products used later in the reduction chain are listed. For the both cases of use of the science recipe all the products are listed.

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9 Pipeline Recipes Interfaces

In this section we provide for each recipe ³ 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.

We also provide a list of the pipeline products for each recipe, indicating their default recipe name, the value of the FITS keyword HIERARCH ESO PRO CATG (in short PRO.CATG) and a short description.

The relevant keywords used to classify each frame are the following:

Association keyword	Information
HIERARCH ESO DPR TYPE	data type
HIERARCH ESO INS MODE	mode
HIERARCH ESO PRO CATG	product category

For each recipe we 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.

The user may obtain a brief description of the main input recipe parameters by typing

```
esorex -help recipe,
```

for example,

```
esorex -help espdr_mdark
```

A possible esorex configuration parameter value is `--suppress-prefix=FALSE`, in which case all products will be renamed with a prefix settable by the parameter `--output-prefix`, defaulted to `out_`, and an increasing number, like `(out_0000.fits, out_0001.fits, out_000N.fits)` For this reason the table briefly describing the products contains also a first column indicating the product ID, which is the value of the product number (with minimum significant digits).

The pipeline performs several quality assessments on the data. The result is stored in a QC keyword that has value "QC <specifier> CHECK", where the <specifier> indicates the kind of check done. A check is successful if the value of the keyword is 1. Some recipe may do several tests. It is also created a keyword "QC <recipe> CHECK", where <recipe> indicates the recipe executed, that indicates the overall product of all checks.

The PRO.CATG chosen for the extracted spectra falls into two groups: 'S2D_*' spectra, that can be of type A or B to represent the object or the calibration fibersi, respectively. These files are 2D images where the rows (Y axis) contain the extracted spectrum of a given order. These are dispersed by the grating and imaged on the detector on different orders. There are 71 orders extracted on fibre A and 70 on fibre B in both modes. Due to the high water vapour absorption around the wavelength of 1.4 micron, there is a gap in the spectral orders. It is impossible to compute the wavelength solution for the faintest order in the gap, therefore this order, with echelle number 105, is skipped and not extracted.

³We do not describe here two recipes: the recipe `espdr_single_bias`, used to reduce HARPS data, and the recipe `espdr_wave_TH_drift`, used for the wavelength calibration when are not available enough good quality FP, FP frames.

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9.1 espdr_mdark

9.1.1 Input

type	TAG	n	setting
raw	DARK	5...n	any
ref	CCD_GEOM	1	match
ref	INST_CONFIG	1	match
ref	ORDERS_MASK	1	match

9.1.2 Output

ID	PRO.CATG	type	Note
0	HOT_PIXEL_MASK	cdb	Hot pixels mask
1	MASTER_DARK	qc	Master dark

9.1.3 Quality control

This recipe computes the following QC parameters (on the image extension n, and read-out region i,j):

QC key name	description
QC EXT _n ROX _i ROY _j DARK MEAN	mean dark [ADU/px/hour]
QC EXT _n ROX _i ROY _j HOTPIX NB	number of hot pixels
QC EXT _n COSMIC RATE PIX	number of cosmic hits per pixel per hour
QC EXT _n COSMIC RATE CM2	number of cosmic hits per cm2 per hour
QC DARK COSMIC CHECK	check on cosmic rate computation results
QC DARK MEAN CHECK	check on mean dark results
QC DARK HOTPIX CHECK	check on hotpixel detection
QC DARK CHECK	overall check on dark

9.1.4 Parameters

parameter name	description
dark_sig_clip_method	method for sigma clipping in master DARK, can be: mean or median. [median]
dark_ksigma	ksigma for sigma clipping in MDARK, must be between: 1.50 and 1000.00. [10.0]
hot_pix_sig_clip_method	method for sigma clipping in HOT PIXELS, can be mean or median. [mean]
hot_pix_ksigma	ksigma for sigma clipping in HOT PIXELS, must be between: 1.50 and 1000.00. [10.0]
hot_pix_max_iter	maximal number of iterations in HOT PIXELS, must be between: 1 and 5000000. [10000]

9.2 espdr_led_ff

9.2.1 Input

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type	TAG	n	setting
raw	LED_FF	10...n ⁴	any
ref	CCD_GEOM	1	match
ref	INST_CONFIG	1	match
ref	ORDERS_MASK	1	match
ref	LED_FF_GAIN_WINDOWS	1	match
cdb	HOT_PIXEL_MASK	1	match
cdb	MASTER_DARK	1	match

9.2.2 Output

ID	PRO.CATG	type	Note
0	BAD_PIXEL_MASK	cdb	Bad pixels mask

9.2.3 Quality control

This recipe computes the following QC parameters (on the image extension n, and read-out region i,j):

QC key name	description
QC EXTn ROXi ROYj MAX FLUX	max flux on raw image [ADU]
QC EXTn ROXi ROYj CONAD	conversion factor [e-/ADU]
QC EXTn ROXi ROYj BADPIX NB	bad pixel number
QC EXTn ROXi ROYj MASTER MAX FLUX	max flux on master [ADU]
QC EXTn ROXi ROYj MASTER MIN FLUX	min flux on master [ADU]
QC EXTn ROXi ROYj MASTER MEAN FLUX	mean flux on master [ADU]
QC MASTER MIN FLUX	overall min flux on master [ADU]
QC MASTER MAX FLUX	overall max flux on master [ADU]
QC SATURATION CHECK	check on frame saturation
QC LEDFF MIN FLUX CHECK	check on minimum flux
QC LEDFF BADPIX CHECK	check on bad pixels
QC LEDFF CONAD CHECK	check on conad
QC LEDFF CHECK	overall check on results

9.2.4 Parameters

parameter name	description
led_ff_sig_clip_method	method for sigma clipping in master LED_FF, can be: mean or median. [median]
led_ff_ksigma	ksigma for sigma clipping in master LED_FF, must be between: 1.50 and 1000.00. [10.0]
bad_pix_sig_clip_method	method for sigma clipping in BAD PIXELS, can be mean or median. [mean]
bad_pix_ksigma	ksigma for sigma clipping in BAD PIXELS, must be between: 1.50 and 1000.00. [10.0]
bad_pix_max_iter	maximal number of iterations in BAD PIXELS, must be between: 1 and 5000000. [10000]

⁴At least five input raw frames for each exposure time, at least two exposure times.

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9.3 espdr_orderdef

9.3.1 Input

type	TAG	n	setting
raw	ORDERDEF_A	1	any
raw	ORDERDEF_B	1	any
ref	CCD_GEOM	1	match
ref	INST_CONFIG	1	match
ref	ORDERS_MASK	1	match
cdb	HOT_PIXEL_MASK	1	match
cdb	MASTER_DARK	1	match
cdb	BAD_PIXEL_MASK	1	match

9.3.2 Output

ID	PRO.CATG	type	Note
0	ORDER_TABLE_A	cdb	Order table tracing fibre A
1	ORDER_TABLE_B	cdb	Order table tracing fibre B

9.3.3 Quality control

This recipe computes the following QC parameters (on the image extension n, order m, and read-out region i,j):

QC key name	description
QC EXTn ROXi ROYj MAX FLUX	max flux on raw image [ADU]
QC ORDERm EXTn POS	order position [pix]
QC ORDERm EXTn RES MIN	min residuals [pix]
QC ORDERm EXTn RES MAX	max residuals [pix]
QC ORDERm EXTn RES STDEV	rms residuals [pix]
QC ORDERm EXTn NB	physical order number
QC ORDER NB	number of orders in the image
QC EXTn ROXi ROYj MAX FLUX	max flux, raw image [ADU]
QC SATURATION CHECK	check on saturation
QC ORDERDEF ORDER CHECK	check on number of detected orders
QC ORDERDEF STDEV CHECK	check on rms residuals
QC ORDERDEF MIN CHECK	check on min residuals
QC ORDERDEF MAX CHECK	check on max residuals
QC ORDERDEF CHECK	overall check

9.3.4 Parameters

There is no user parameters for orderdef recipe.

9.4 espdr_mflat

9.4.1 Input

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type	TAG	n	bin
raw	FLAT_A	5...n	any
raw	FLAT_B	5...n	any
ref	CCD_GEOM	1	match
ref	INST_CONFIG	1	match
ref	ORDERS_MASK	1	match
ref	STATIC_WAVE_MATRIX_A	1	match
ref	STATIC_WAVE_MATRIX_B	1	match
ref	STATIC_DLL_MATRIX_A	1	match
ref	STATIC_DLL_MATRIX_B	1	match
cdb	HOT_PIXEL_MASK	1	match
cdb	MASTER_DARK	1	match
cdb	BAD_PIXEL_MASK	1	match
cdb	ORDER_TABLE_A	1	match
cdb	ORDER_TABLE_B	1	match

9.4.2 Output

ID	PRO.CATG	type	Note
0	FF_BACKGROUND_MAP_A	cdb	Background map for fibre A
1	FS2D_A	cdb	Order by order extracted spectrum for fibre A
2	BLAZE_A	cdb	Blaze for fibre A
3	FSPECTRUM_A	cdb	Order by order extracted spectrum for fibre A
4	ORDER_PROFILE_A	cdb	Order profile for fibre A
5	FF_BACKGROUND_MAP_B	cdb	Background map for fibre B
6	FS2D_B	cdb	Order by order extracted spectrum for fibre B
7	BLAZE_B	cdb	Blaze for fibre B
8	FSPECTRUM_B	cdb	Order by order extracted spectrum for fibre B
9	ORDER_PROFILE_B	cdb	Order profile for fibre B

9.4.3 Quality control

This recipe computes the following QC parameters (on the image extension n, order m, and read-out region i,j):

QC key name	description
QC EXT _n ROX _i ROY _j MAX FLUX	max flux on raw image [ADU]
QC ORDER _m FLAT RMS	FLAT RMS in the order
QC ORDER _m SNR	SNR in the order
QC ORDER _m COSMIC NB	cosmics number in the order
QC EXT _n ROX _i ROY _j MAX FLUX	max flux, raw image [ADU]
QC EXT _n BKGR MEAN	bkgr mean in the extension [e-]
QC EXT _n BKGR MIN	bkgr min in the extension [e-]
QC EXT _n BKGR MAX	bkgr max in the extension [e-]
QC SATURATION CHECK	quality check on saturation
QC FLAT RMS CHECK	quality check on rms
QC FLAT SNR CHECK	quality check on SNR
QC FLAT BKGR CHECK	background quality check
QC FLAT CHECK	overall quality check

9.4.4 Parameters

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parameter name	description
flat_sig_clip_method	method for sigma clipping in master FLAT, can be: mean or median. [median]
flat_ksigma	ksigma for sigma clipping in MFLAT, must be between: 1.50 and 1000.00. [10.0]
background_sw	background measurement activation (on/off). [on]
bkgr_grid_size_x	grid size in x used to calculate the background, between: 16 and 10000. [577]
bkgr_grid_size_y	grid size in y used to calculate the background, between: 16 and 10000. [256]
flat_extraction_method	Method used to extract orders. [horne]
flat_extraction_ksigma	ksigma for extraction, must be between: -1.00 and 20.00. [-1.0]

9.5 espr_wave_FP

9.5.1 Input

type	TAG	n	setting
raw	FP_FP	1	any
ref	CCD_GEOM	1	match
ref	INST_CONFIG	1	match
ref	ORDERS_MASK	1	match
cdb	HOT_PIXEL_MASK	1	match
cdb	MASTER_DARK	1	match
cdb	BAD_PIXEL_MASK	1	match
cdb	ORDER_TABLE_A	1	match
cdb	ORDER_TABLE_B	1	match
cdb	ORDER_PROFILE_A	1	match
cdb	ORDER_PROFILE_B	1	match
cdb	F_SPECTRUM_A	1	match
cdb	F_SPECTRUM_B	1	match
cdb	BLAZE_A	1	match
cdb	BLAZE_B	1	match

9.5.2 Output

ID	PRO.CATG	type	Note
0	S2D_BLAZE_FP_FP_A	cdb	S2D Extracted blaze for fibre A
1	S2D_FP_FP_A	cdb	S2D Extracted spectrum for fibre A
2	FP_SEARCHED_LINE_TABLE_FP_FP_A	cdb	Detected FP peaks on fibre A
3	S2D_BLAZE_FP_FP_B	cdb	S2D Extracted blaze for fibre B
4	S2D_FP_FP_B	cdb	S2D Extracted spectrum for fibre B
5	FP_SEARCHED_LINE_TABLE_FP_FP_B	cdb	Detected FP peaks on fibre B

9.5.3 Quality control

This recipe computes the following QC parameters (on the image extension n, order m, and read-out region i,j):

QC key name	description
QC EXT _n ROX _i ROY _j MAX FLUX	max flux on raw image [ADU]
QC ORDER _m COSMIC NB	number of cosmics detected in order m
QC SATURATION CHECK	quality check on saturation
QC COSMIC NB	number of cosmics
QC WAVE CHECK	overall quality check

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9.5.4 Parameters

parameter name	description
fp_extraction_method	method used to extract orders. [horne]
fp_extraction_ksigma	ksigma for extraction, must be between: -2.00 and 20.00. [5.0]

9.6 espdr_wave_THAR

9.6.1 Input

type	TAG	n	setting
raw	THAR_FP	1	any
ref	CCD_GEOM	1	match
ref	INST_CONFIG	1	match
ref	ORDERS_MASK	1	match
ref	STATIC_DLL_MATRIX_A	1	match
ref	STATIC_WAVE_MATRIX_A	1	match
ref	REF_LINE_TABLE_A	1	match
cdb	HOT_PIXEL_MASK	1	match
cdb	MASTER_DARK	1	match
cdb	BAD_PIXEL_MASK	1	match
cdb	ORDER_TABLE_A	1	match
cdb	ORDER_TABLE_B	1	match
cdb	ORDER_PROFILE_A	1	match
cdb	ORDER_PROFILE_B	1	match
cdb	FSPECTRUM_A	1	match
cdb	FSPECTRUM_B	1	match
cdb	BLAZE_A	1	match
cdb	BLAZE_B	1	match
cdb	S2D_BLAZE_FP_FP_B	1	match
cdb	FP_SEARCHED_LINE_TABLE_FP_FP_A	1	match

And for the other fibre a similar input where THAR_FP is replaced by FP_THAR, STATIC_WAVE/DLL_MATRIX_A are replaced by STATIC_WAVE/DLL_MATRIX_B, FP_SEARCHED_LINE_TABLE_FP_FP_A is replaced by FP_SEARCHED_LINE_TABLE_FP_FP_B and REF_LINE_TABLE_A is replaced by REF_LINE_TABLE_B

9.6.2 Output

ID	PRO.CATG	type	Note
0	S2D_BLAZE_THAR_FP_A	cdb	S2D Extracted blaze for fibre A
1	S2D_THAR_FP_A	cdb	S2D Extracted spectrum for fibre A
2	WAVE_MATRIX_THAR_FP_A	cdb	Wave map (vacuum) for fibre A
3	AIR_WAVE_MATRIX_THAR_FP_A	cdb	Wave map (air) for fibre A
4	DLL_MATRIX_THAR_FP_A	cdb	DLL map (vacuum) fibre A
5	AIR_DLL_MATRIX_THAR_FP_A	cdb	DLL map (air) fibre A
6	WAVE_TABLE_THAR_FP_A	cdb	Table of coefficients of the wave sol fit for each order
7	FP_FITTED_LINE_TABLE_THAR_FP_A	cdb	Table of fitted FP lines used in the wave. sol. for fibre A
8	THAR_LINE_TABLE_THAR_FP_A	cdb	ThAr line table for fibre A
9	LINE_TABLE_RAW_THAR_FP_A	cdb	Table of ThAr lines fitted on the raw frame for fibre A
10	S2D_BLAZE_THAR_FP_B	cdb	S2D Extracted blaze for fibre B
11	S2D_THAR_FP_B	cdb	S2D Extracted spectrum for fibre B

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DLL files contain pixel widths in wavelength units. For the FP_THAR reduction the pipeline products have similar PRO.CATGs except that from Id 4 on they refer to fibre B instead of A.

9.6.3 Quality control

This recipe computes the following QC parameters (on the image extension n, order m, and read-out region i,j):

QC key name	description
QC DRIFT DETn SLOPE_O	Drift slope across the orders per detector
QC DRIFT DETn SLOPE_O_ERR	Drift slope error
QC DRIFT DETn SLOPE_X	Drift slope along the orders per detector
QC DRIFT DETn SLOPE_X_ERR	Drift slope error
QC DRIFT DETn CHISQ	CHI2 of the drift fit
QC DRIFT DETn REJECTED	nb of rejected pixels
QC DRIFT DETn MEAN	mean drift per detector
QC DRIFT DETn MEAN_ERR	mean drift error
QC DRIFT DETn FLUX_RATIO	flux ratio per detector
QC DRIFT DETn FLUX_RATIO_ERR	flux ratio error
QC DRIFT DETn FIRST_ORDER	first order on the detector
QC DRIFT DETn LAST_ORDER	last order on the detector
QC DRIFT CHI2 CHECK	quality check on the drift
QC ORDERm FP LINES NB	number of valid FP lines in order m
QC ORDERm CHI2	reduced CHI2 of ll solution for order m
QC ORDERm RMS	dispersion of residuals around mean
QC THAR RESOL MEDIAN	ThAr lines resolution median
QC THAR SATUR LINES NB	saturated ThAr lines number
QC THAR LINES NB	Valid ThAr lines number
QC THAR FLUX RATIO MEDIAN	Thar lines flux ratio median
QC THAR RV DIFF MEDIAN	[m/s] Thar lines RV difference median
QC FP D OFFSET	[Angstrom] D(lambda) offset
QC FP D OFFSET ERROR	[Angstrom] D(lambda) offset error
QC FP D OFFSET RMS	[Angstrom] D(lambda) offset RMS
QC FP LINES NB	Valid FP lines number
QC LINES ORDER MIN CHECK	quality check on min order residuals
QC LINES TOT CHECK	quality check on total lines number
QC FP CHI2 CHECK	quality check on chi2
QC FP RMS CHECK	quality check on rms THAR
QC THAR RESOL CHECK	quality check on resolution
QC THAR FLUX RATIO CHECK	QC on TH lines flux ratio
QC FP SOL QUAL CHECK	quality check on wave sol quality
QC WAVE CHECK	overall quality check

9.6.4 Parameters

parameter name	description
thar_extraction_method	Method used to extract orders. [horne]
thar_extraction_ksigma	ksigma for extraction, must be between: -2.00 and 20.00. [-1.0]
d_fit_poly_deg	d fit poly deg in wave_THAR, must be between: 1 and 50. [25]
d_fit_small_res_limit	d fit small res_limit in wave_THAR, must be between: 99 and 99. [10.0]
wave_sol_poly_deg	wavelength solution poly deg in wave_THAR, must be between: 1 and 1. [10]

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9.7 espdr_wave_LFC

9.7.1 Input

type	TAG	n	setting
raw	FP_LFC	1	any
ref	CCD_GEOM	1	match
ref	INST_CONFIG	1	match
ref	ORDERS_MASK	1	match
cdb	HOT_PIXEL_MASK	1	match
cdb	MASTER_DARK	1	match
cdb	BAD_PIXEL_MASK	1	match
cdb	ORDER_TABLE_A	1	match
cdb	ORDER_TABLE_B	1	match
cdb	ORDER_PROFILE_A	1	match
cdb	ORDER_PROFILE_B	1	match
cdb	FSPECTRUM_A	1	match
cdb	FSPECTRUM_B	1	match
cdb	BLAZE_A	1	match
cdb	BLAZE_B	1	match
cdb	DLL_MATRIX_THAR_FP_A	1	match
cdb	WAVE_MATRIX_THAR_FP_A	1	match

And for the other fibre a similar input where FP_LFC is replaced by LFC_FP and the WAVE and DLL MATRIXEs for FP_THAR are used instead the THAR_FP ones.

9.7.2 Output

ID	PRO.CATG	type	Note
0	S2D_BLAZE_LFC_FP_A	cdb	S2D Extracted blaze for fibre A
1	S2D_LFC_FP_A	cdb	S2D Extracted spectrum for fibre A
2	WAVE_MATRIX_LFC_FP_A	cdb	Wave map (vacuum) for fibre A
3	AIR_WAVE_MATRIX_LFC_FP_A	cdb	Wave map (air) for fibre A
4	DLL_MATRIX_LFC_FP_A	cdb	DLL map (vacuum) fibre A
5	AIR_DLL_MATRIX_LFC_FP_A	cdb	DLL map (air) fibre A
6	WAVE_TABLE_LFC_FP_A	cdb	Table of coefficients of the wave sol fit for each order
7	LFC_FITTED_LINE_TABLE_LFC_FP_A	cdb	Table of fitted LFC lines used in the wave. sol. for fibre A
8	S2D_BLAZE_LFC_FP_B	cdb	S2D Extracted blaze for fibre B
9	S2D_LFC_FP_B	cdb	S2D Extracted spectrum for fibre B

For the FP_LFC reduction the pipeline products have similar PRO.CATGs except that from Id 4 on they refer to fibre B instead of A.

9.7.3 Quality control

This recipe computes the following QC parameters (on the image extension n, order m, and read-out region i,j):

QC key name	description
QC EXTn ROXi ROYj MAX FLUX	max flux in the raw image [ADU]
QC ORDERm COSMIC NB	number of detected cosmics in order m
QC COSMIC NB	total number of detected cosmics
QC ORDERm LFC LINES NB	number of valid lines in order m

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QC ORDER _m CHI2	reduced CHI2 of ll solution for order m
QC ORDER _m RMS	dispersion of residuals around mean
QC ORDER _m LFC FIT WAVE	flag indicating if the wave sol was fitted with LFC for order m
QC LFC LINES NB	total number of valid LFC lines
QC LFC LINES ORDER MIN CHECK	quality check on min number of LFC lines per order
QC LFC LINES TOT CHECK	quality check on total detected lines number
QC LFC CHI2 CHECK	quality check on CHI2 of wave sol
QC LFC RMS CHECK	quality check on RMS of wave sol
QC SATURATION CHECK	check on saturation
QC LFC WAVE CHECK	overall quality check

9.7.4 Parameters

parameter name	description
lfc_extraction_method	method used to extract orders. [horne]
lfc_extraction_ksigma	ksigma for extraction, must be between: -1.00 and 20.00. [10.0]
wave_sol_poly_deg	wavelength solution polynomial degree in wave_THAR, must be between: 3 and 10. [7]

9.8 espdr_cal_contam

9.8.1 Input

type	TAG	n	setting
raw	RAW_CONTAM_FP	1	any
ref	CCD_GEOM	1	match
ref	INST_CONFIG	1	match
ref	ORDERS_MASK	1	match
cdb	HOT_PIXEL_MASK	1	match
cdb	MASTER_DARK	1	match
cdb	BAD_PIXEL_MASK	1	match
cdb	ORDER_TABLE_A	1	match
cdb	ORDER_TABLE_B	1	match
cdb	ORDER_PROFILE_A	1	match
cdb	ORDER_PROFILE_B	1	match
cdb	F SPECTRUM_A	1	match
cdb	F SPECTRUM_B	1	match

9.8.2 Output

ID	PRO.CATG	type	Note
0	CONTAM_S2D_A	qc	S2D Extracted spectrum for fibre A
1	CONTAM_S2D_B	qc	S2D Extracted spectrum for fibre B
2	CONTAM_FP	cdb	contamination of fibre B on fibre A

9.8.3 Quality control

This recipe computes the following QC parameters (on the image extension n, order m, and read-out region i,j):

QC key name	description
-------------	-------------

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QC EXT _n ROX _i ROY _j MAX FLUX	max flux, raw image
QC SATURATION CHECK	quality check on saturation
QC ORDER _m MAX FLUX	S2D flux max, fibre A
QC CONTAM FLUX CHECK	quality check on flux
QC CONTAM CHECK	overall quality check

9.8.4 Parameters

parameter name	description
background_sw	if on (default value) then background is subtracted, 1=on 0=off. [0]
contam_bkgr_grid_size_x	Grid size in x used to calculate the background, between: 128 and 512. [577]
contam_bkgr_grid_size_y	Grid size in y used to calculate the background, between: 128 and 512. [256]
contam_extraction_method	Method used to extract orders. [horne]
contam_extraction_ksigma	ksigma used to extract orders. [3.5]

9.9 espdr_cal_eff_ab

9.9.1 Input

type	TAG	n	setting
raw	EFF_AB	1	any
ref	CCD_GEOM	1	match
ref	ORDERS_MASK	1	match
ref	INST_CONFIG	1	match
cdb	HOT_PIXEL_MASK	1	match
cdb	MASTER_DARK	1	match
cdb	BAD_PIXEL_MASK	1	match
cdb	ORDER_TABLE_A	1	match
cdb	ORDER_TABLE_B	1	match
cdb	ORDER_PROFILE_A	1	match
cdb	ORDER_PROFILE_B	1	match
cdb	FSPECTRUM_A	1	match
cdb	FSPECTRUM_B	1	match

9.9.2 Output

ID	PRO.CATG	type	Note
0	S2D_BLAZE_EFF_A	qc	S2D extracted blaze spectrum for fibre A
1	S2D_BLAZE_EFF_B	qc	S2D extracted blaze spectrum for fibre B
2	REL_EFF_B	cdb	spectrum describing the trasmission ratio fibre B/fibre A in pixel units.

9.9.3 Quality control

This recipe computes the following QC parameters (on the image extension n, order m, and read-out region i,j):

QC key name	description
QC EXT _n ROX _i ROY _j MAX FLUX	max flux, raw image [ADU]
QC SATURATION CHECK	check on saturation

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QC EXT _n BKGR MEAN	bkgr mean in the extension [e-]
QC EXT _n BKGR MIN	bkgr min in the extension [e-]
QC EXT _n BKGR MAX	bkgr max in the extension [e-]
QC EFFAB BKGR CHECK	check on background level
QC ORDER _m SNR	SNR in the order m
QC ORDER _m COSMIC NB	cosmics number in the order
QC EFFAB SNR CHECK	check on SNR
QC REL EFF MIN	min relative efficiency
QC REL EFF MAX	max relative efficiency
QC REL EFF MIN CHECK	check on computation min efficiency
QC REL EFF MAX CHECK	check on computation max efficiency
QC EFFAB CHECK	overall check on effab products

9.9.4 Parameters

parameter name	description
eff_ab_bkgr_grid_size_x	Grid size in x used to calculate the background, between: 128 and 512. [577]
eff_ab_bkgr_grid_size_y	Grid size in y used to calculate the background, between: 128 and 512. [256]
eff_ab_extraction_method	Method used to extract orders. [horne]
eff_ab_extraction_ksigma	ksigma used to extract orders. [5.0]
eff_ab_poly_deg	Efficiency computation fit polynomial degree. [3]

9.10 espdr_cal_flux

9.10.1 Input

type	TAG	n	setting
raw	FLUX	1	any
ref	CCD_GEOM	1	match
ref	INST_CONFIG	1	match
ref	ORDERS_MASK	1	match
ref	EXT_TABLE	1	match
ref	STD_TABLE	1	match
cdb	HOT_PIXEL_MASK	1	match
cdb	MASTER_DARK	1	match
cdb	BAD_PIXEL_MASK	1	match
cdb	ORDER_TABLE_A	1	match
cdb	ORDER_TABLE_B	1	match
cdb	ORDER_PROFILE_A	1	match
cdb	ORDER_PROFILE_B	1	match
cdb	FSPECTRUM_A	1	match
cdb	FSPECTRUM_B	1	match
cdb	BLAZE_A	1	match
cdb	BLAZE_B	1	match
cdb	WAVE_MATRIX_THAR_FP_A	1	match
cdb	WAVE_MATRIX_FP_THAR_B	1	match
cdb	DLL_MATRIX_THAR_FP_A	1	match
cdb	DLL_MATRIX_FP_THAR_B	1	match

9.10.2 Output

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ID	PRO.CATG	type	Note
0	S2D_STD_A	qc	S2D Extracted spectrum for fibre A
1	S1D_STD_A	qc	S1D Extracted spectrum for fibre A
2	S1D_ENERGY_STD_A	cdb	S1D energy for fibre A
3	S2D_BLAZE_STD_A	cdb	S2D blaze spectrum for fibre A
4	AVG_FLUX_STD_A	cdb	average flux for fibre A
5	ABS_EFF_RAW_A	cdb	absolute raw efficiency for fibre A
6	ABS_EFF_A	cdb	absolute efficiency for fibre A

9.10.3 Quality control

This recipe computes the following QC parameters (on the image extension n, order m, and read-out region i,j):

QC key name	description
QC EXTn ROXi ROYj MAX FLUX	max flux, raw image [ADU]
QC SATURATION CHECK	saturation [ADU] QC
QC ORDERm COSMIC NB	cosmics number in the order m
QC ORDERm SNR	SNR in the order m
QC CALFLUX SNR CHECK	check on SNR computed value
QC EXTn BKGR MEAN	bkgr mean in the extension [e-]
QC EXTn BKGR MIN	bkgr min in the extension [e-]
QC EXTn BKGR MAX	bkgr max in the extension [e-]
QC MIN RAW ABS EFF	min raw absolute efficiency
QC MAX RAW ABS EFF	max raw absolute efficiency
QC MEAN RAW ABS EFF	mean raw absolute efficiency
QC MIN EXTCORR ABS EFF	minimum extinction-corrected abs eff
QC MAX EXTCORR ABS EFF	maximum extinction-corrected abs eff
QC MEAN EXTCORR ABS EFF	mean extinction-corrected abs eff
QC MIN ABS EFF	minimum absolute efficiency
QC MAX ABS EFF	maximum absolute efficiency
QC MEAN ABS EFF	mean absolute efficiency
QC MIN ABS EFF CHECK	minimum absolute efficiency check
QC MAX ABS EFF CHECK	maximum absolute efficiency check
QC BERV ⁵	barycentric correction [km s ⁻¹]
QC BJD	barycentric Julian date (TDB) [JD]
QC BERVMAX	barycentric max [km s ⁻¹]
QC CALFLUX SEEING KW CHECK	check on seeing
QC CALFLUX CHECK	overall check on recipe

9.10.4 Parameters

parameter name	description
background_sw	if 1 (default value) then background is subtracted, 1=on 0=off. [0]
bkgr_grid_size_x	Grid size in x used to calculate the background, between: 128 and 512. [577]
bkgr_grid_size_y	Grid size in y used to calculate the background, between: 128 and 512. [256]
flux_extraction_method	Method used to extract orders. [horne]
flux_extraction_ksigma	ksigma used to extract orders. [3.5]
flux_poly_deg	Efficiency computation fit polynomial degree. [6]

⁵Barycentric Earth Radial Velocity (BERV)

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9.11 espdr_sci_red

9.11.1 Input

type	TAG	n	setting
raw	OBJ_FP	1	any
ref	CCD_GEOM	1	match
ref	INST_CONFIG	1	match
ref	ORDERS_MASK	1	match
ref	MASK_TABLE	11	match
ref	EXT_TABLE	1	match
ref	MASK_LUT	1	match
ref	FLUX_TEMPLATE	1	match
cdb	HOT_PIXEL_MASK	1	match
cdb	MASTER_DARK	1	match
cdb	BAD_PIXEL_MASK	1	match
cdb	ORDER_TABLE_A	1	match
cdb	ORDER_TABLE_B	1	match
cdb	ORDER_PROFILE_A	1	match
cdb	ORDER_PROFILE_B	1	match
cdb	FSPECTRUM_A	1	match
cdb	FSPECTRUM_B	1	match
cdb	BLAZE_A	1	match
cdb	BLAZE_B	1	match
cdb	WAVE_MATRIX_THAR_FP_A	1	match
cdb	WAVE_MATRIX_FP_THAR_B	1	match
cdb	DLL_MATRIX_THAR_FP_A	1	match
cdb	DLL_MATRIX_FP_THAR_B	1	match
cdb	S2D_BLAZE_THAR_FP_B	1	match
cdb	WAVE_MATRIX_LFC_FP_A	? ⁶	match
cdb	WAVE_MATRIX_FP_LFC_B	?	match
cdb	DLL_MATRIX_LFC_FP_A	?	match
cdb	DLL_MATRIX_FP_LFC_B	?	match
cdb	CONTAM_FP	?	match
cdb	REL_EFF_B	1	match
cdb	ABS_EFF_A	?	match

For the observations with sky on fibre B - OBJ_SKY, the inputs for drift computation (S2D_BLAZE_THAR_FP_B) and the contamination (CONTAM_FP) are not needed. Note that there can be cross-talk from the object fibre to the sky fibre of up to 1%. This contamination is not corrected for and is thus over-subtracted in the SKYSUB frames.

The LFC products are needed if the user wishes to use the LFC wavelength calibration products. In this case s/he has to set the parameter `wave_cal_source` to LFC. Even if the WAVE/DLL_MATRIX_THAR_FP/FP_THAR are provided, they will not be used in this case.

9.11.2 Output for OBJ_FP

ID	PRO.CATG	type	Note
0	CCF_RESIDUALS_A	qc	residuals from CCF computation
1	DRIFT_MATRIX_B	qc	drift matrix relative to fibre B
2	S2D_BLAZE_A	cdb	S2D spectrum blaze fibre A
3	S2D_A	cdb	S2D spectrum for fibre A

⁶? indicates an optional input

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4	S2D_BLAZE_B	cdb	S2D spectrum blaze fibre B
5	S2D_B	cdb	S2D spectrum for fibre B
6	S1D_FLUXCAL_A	cdb	S1D flux calibrated spectrum for fibre A
7	S1D_A	cdb	S1D spectrum for fibre A
8	S1D_FINAL_A	cdb	table containing all above S1D products for fibre A. The format is compatible with ESO archive standard.
9	S1D_B	cdb	S1D spectrum for fibre B
10	S1D_FINAL_B	cdb	table containing all above S1D products for fibre B.
11	CCF_A	cdb	CCF for fibre A
12	CCD_CORR_SCIENCE	-	frame on which cosmics are detected. ⁷
13	CRH_MAP	-	(van-dokkum) cosmic detection map ⁸
14	FCRH_MAP	-	post filtered cosmic detection map ⁹

If the user does not provide `ABS_EFF_A` optional input frame the “FLUXCAL” products are not created.

The ‘S2D_*’ data products contain the extracted spectrum order by order or slice (depending on the mode), the associated error and quality pixel map in the extensions SCIDATA, ERRDATA, QUALDATA respectively. The ‘S2D_*’ products also contain the wavelength solutions and the detector pixels sizes computed in vacuum and air in the extensions `WAVEDATA_VAC_BARY`, `WAVEDATA_AIR_BARY`, `DLLDATA_VAC_BARY`, `DLLDATA_AIR_BARY`, respectively.

The ‘S1D_*’ product tables provides the wavelength solution (in vacuum and air), the merged spectrum resampled to an equidistant grid, its error and pixel quality flag.

The `S1D_FINAL_B` product table contains the same information as the S1D products, in Phase3 compliant data format. It also includes the computed Signal to Noise ratio (SNR).

The fibre `S1D_FINAL_A` product table includes the flux calibrated (and, when available, sky subtracted) object spectrum, the SNR, and information on the flux in electrons (and eventually the one of the sky spectrum) together with the associated error and pixel quality.

The `CCF_A` data contains the computed CCF for each order and the associated error and pixel quality for each order/slice (depending on the mode) and an additional first row for the weighted sum of the CCF.

9.11.3 Output for *OBJ_SKY*

ID	PRO.CATG	type	Note
0	CCF_RESIDUALS_A	qc	residuals from CCF computation
1	S2D_SKYSUB_A	cdb	S2D spectrum sky-subtracted for fibre A
2	S2D_BLAZE_A	cdb	S2D spectrum blaze fibre A
3	S2D_A	cdb	S2D spectrum for fibre A
4	S2D_BLAZE_B	cdb	S2D spectrum blaze fibre B
5	S2D_B	cdb	S2D spectrum for fibre B
6	S1D_SKYSUB_A	cdb	S1D spectrum sky-subtracted for fibre A
7	S1D_FINAL_A	cdb	table containing all above S1D products for fibre A. The format is compatible with ESO archive standard.
8	S1D_SKYSUB_FLUXCAL_A	cdb	S1D spectrum sky-subtracted flux calibrated for fibre A
9	S1D_A	cdb	S1D spectrum for fibre A
10	S1D_FLUXCAL_A	cdb	S1D flux calibrated spectrum for fibre A
11	S1D_B	cdb	S1D spectrum for fibre B
12	S1D_FINAL_B	cdb	table containing all above S1D products for fibre B.
13	CCF_A	cdb	CCF for fibre A
14	CCF_B	cdb	CCF for fibre B

⁷ optional product to inspect cosmic detection obtained if `extra_products_sw` is set to True

⁸ optional product to inspect cosmic detection obtained if `extra_products_sw` is set to True

⁹ optional product to inspect cosmic detection obtained if `extra_products_sw` is set to True and `-lacosmic.post-filter-x/y` are ≥ 1

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If the user does not provide ABS_EFF_A optional input frame the “FLUXCAL” products are not created.

9.11.4 Quality control

This recipe computes the following QC parameters (on the image extension n, order m, and read-out region i,j):

QC key name	description
QC EXTn ROXi ROYj BIAS RON	RON[ADU]
QC EXTn ROXi ROYj MAX FLUX	max flux, raw image [ADU]
QC SATURATION CHECK	saturation [ADU] QC
QC ORDERm SNR	SNR in the order m
QC ORDERm COSMIC NB	cosmics number in the order m
QC ORDERm COSMIC NB2	Additional cosmics found in each order
QC ORDERm FLUX CORR	flux correction for the order m
QC FLUX CORR MIN	min of flux correction
QC FLUX CORR MAX	max of flux correction
QC SCIRED FLUX CORR CHECK	flux correction QC
QC DRIFT DETn SLOPE_O	Drift slope across the orders per detector
QC DRIFT DETn SLOPE_O_ERR	Drift slope error
QC DRIFT DETn SLOPE_X	Drift slope along the orders per detector
QC DRIFT DETn SLOPE_X_ERR	Drift slope error
QC DRIFT DETn CHISQ	CHI2 of the drift fit
QC DRIFT DETn REJECTED	nb of rejected pixels
QC DRIFT DETn MEAN	mean drift per detector
QC DRIFT DETn MEAN_ERR	mean drift error
QC DRIFT DETn FLUX_RATIO	flux ratio per detector
QC DRIFT DETn FLUX_RATIO_ERR	flux ratio error
QC DRIFT DETn FIRST_ORDER	first order on the detector
QC DRIFT DETn LAST_ORDER	last order on the detector
QC DRIFT CHI2 CHECK	quality check on the drift
QC BERV ¹⁰	barycentric correction [km s ⁻¹]
QC BJD	barycentric Julian date (TDB) [JD]
QC BERVMAX	barycentric max [km s ⁻¹]
QC EXTn BKGR MEAN	bkgr mean in the extension [e-]
QC EXTn BKGR MIN	bkgr min in the extension [e-]
QC EXTn BKGR MAX	bkgr max in the extension [e-]
QC CCF RV	radial velocity [km s ⁻¹]
QC CCF RV ERROR	error on Radial velocity [km s ⁻¹]
QC CCF FWHM	CCF FWHM [km s ⁻¹]
QC CCF FWHM ERROR	CCF FWHM error [km s ⁻¹]
QC CCF CONTRAST	CCF contrast
QC CCF CONTRAST ERROR	CCF contrast error
QC CCF CONTINUUM	CCF continuum level [e-]
QC CCF MASK	CCF mask used
QC CCF FLUX ASYMMETRY	CCF asymmetry [km s ⁻¹]
QC CCF FLUX ASYMMETRY ERROR	CCF asymmetry error [km s ⁻¹]
QC CCF BIS SPAN	CCF bisector span (km s ⁻¹)
QC CCF BIS SPAN ERROR	CCF bisector span error [km s ⁻¹]
QC SCIRED CHECK	overall science check

Please note that previous list refers to the case of SCIENCE_FP. In case of SCIENCE_SKY, there is no drift computation, nor corresponding check. Moreover in that case S2D_BLAZE_THAR_FP is not a necessary input.

¹⁰Barycentric Earth Radial Velocity (BERV)

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9.11.5 Parameters

parameter name	description
wave_cal_source	Wavelength calibration source to be used on science fiber ('THAR' or 'LFC'). [THAR]
ksigma_cosmic	ksigma for removing cosmics on fiber A or SKY, -1.0 - no cosmics removal. [3.5]
rv_center	Approximate RV in km s ⁻¹ . In case of default (-9999) the pipeline will use the value of the FITS keyword OCS OBJ RV. [-9999.0]
rv_range	Half Range for the RV table [km s ⁻¹]. [20.0]
rv_step	Range's step for the RV table [km s ⁻¹]. [0.5]
mask_table_id	Mask table to be used, defined by it's spectral type Id, e.g. 'F9', 'G2', 'G8', 'G9', 'K2', 'K6', or 'M2'. In case of default ('XX') the pipeline will read the value of the FITS keyword OCS OBJ SP TYPE and uses a correspondence table to assign the closest available mask to the spectral type given by the FITS keyword or the user. [XX] If none specified, the G2 is used.
extraction_method	Method used to extract orders: 'horne' or 'simple' [horne]
background_sw	Background measurement activation (on/off). [on]
flux_correction_type	Flux correction: NONE, AUTO or <spectral_type>. [AUTO]
drift_correction_sw	Drift correction activation (on/off). [on]
bias_res_removal_sw	Flag indicating to remove or not MB residuals. [on]
sci_bkgr_grid_size_x	Grid size in x used to calculate the background, between: 16 and 10000. [577]
sci_bkgr_grid_size_y	Grid size in y used to calculate the background, between: 16 and 10000. [256]
drift_method_fp	Method adopted to compute drift. [flux_global_drift_global_sequential_fit]
drift_space	Space to compute drift (pixel/velocity). [pixel]
drift_ksigma	ksigma for computing drift, -1.0 - no ksigma clip. [50.0]
sky_sub_method	Method used to subtract the sky (pixel-by-pixel/smoothed). [pixel-by-pixel]
sky_sub_sliding_box_size	Sliding box size in smoothed sky subtraction. [50]
slit_loss	Slit loss correction in flux calibration. [-1.0]. A null or negative value calculates the correction from the seeing (FWHM.IA header keyword). A positive value indicates the correction to apply (the flux calibrated spectrum will be divided by the value specified by the parameter) instead of the one computed by the seeing. For OBJ,SKY observations, the correction is applied only to sky-subtracted products.
cosmic_detection_sw	LA Cosmic detection activation switch. [0]
lacosmic.post-filter-x	X Size of the post filtering kernel. [0]
lacosmic.post-filter-y	Y Size of the post filtering kernel. [0]
lacosmic.post-filter-mode	Post filtering mode. [dilation]
lacosmic.sigma_lim	LA Cosmic Poisson fluctuation threshold. [4.0]
lacosmic.f_lim	LA Cosmic minimum contrast. [4.0]
lacosmic.max_iter	LA Cosmic max number of iterations. [5]
extra_products_sw	Set to TRUE to create extra products to inspect LA Cosmic results. [FALSE]

9.12 espdr_compu_drift

The compu_drift recipe is not part of the reduction cascade. It allows to compute the drift on any sequence of the S2D_BLAZE spectra. It can be launched by hand, e.g. with esorex.

9.12.1 Input

type	TAG	n	setting
cdb	S2D_BLAZE*	2..n	any
ref	CCD_GEOM	1	match
ref	INST_CONFIG	1	match
cdb	WAVE_MATRIX*	1	match
cdb	DLL_MATRIX*	1	match

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The drift is computed on the calibration source (THAR, FP or LFC) S2D de-flattened, non de-blazed spectra. For example, to compute the drift with fibre B on FP, input files can be of type OBJ_FP, THAR_FP, FP_FP. The WAVE and DLL MATRIXEs have to match the fibre for which the drift is computed, in the case of fibre B on FP it should be *MATRIX_FP_THAR_B. The first frame in the S2D list is the reference frame for the drift calculation.

9.12.2 Output

ID	PRO.CATG	type	Note
0	DRIFT_<calib_source_A_and_B>_0	qc	Drift computed for the slice 0
1	DRIFT_<calib_source_A_and_B>_1	qc	Drift computed for the slice 1

9.12.3 Quality control

This recipe computes the following QC parameters (on the image extension n, order m, and read-out region i,j):

QC key name	description
QC DRIFT REF_ARC_FILE	Reference for drift computation
QC DRIFT METHOD	Drift method used
QC DRIFT SPACE	Drift space used
QC DRIFT DETn SLOPE_O	Drift slope across the orders per detector
QC DRIFT DETn SLOPE_O_ERR	Drift slope error
QC DRIFT DETn SLOPE_X	Drift slope along the orders per detector
QC DRIFT DETn SLOPE_X_ERR	Drift slope error
QC DRIFT DETn CHISQ	CHI2 of the drift fit
QC DRIFT DETn REJECTED	nb of rejected pixels
QC DRIFT DETn MEAN	mean drift per detector
QC DRIFT DETn MEAN_ERR	mean drift error
QC DRIFT DETn FLUX_RATIO	flux ratio per detector
QC DRIFT DETn FLUX_RATIO_ERR	flux ratio error
QC DRIFT DETn FIRST_ORDER	first order on the detector
QC DRIFT DETn LAST_ORDER	last order on the detector

9.12.4 Parameters

parameter name	description
method_thar	method for drift computation for ThAr spectrum [flux_global_drift_global_sequential_fit]
method_fp	method for drift computation for FP spectrum [flux_global_drift_global_sequential_fit]
method_lfc	method for drift computation for LFC spectrum [flux_global_drift_global_sequential_fit]
space	Type of drift computation: ni the space of pixels or velocities [pixel]
ksig	ksigma for rejecting outliers o=in the drift fit [50.0]
max_flux_threshold	Maximum allowed flux [700000.0]
min_flux_threshold	Minimum allowed flux [1000.0]

9.12.5 Example

Here is the SOF example of the compu_drift recipe. The S2Ds are extracted S2D spectra of a calibration source FP on fibre A. The first frame in the S2D list is the reference frame for the drift calculation. The WAVE_MATRIX and the DLL_MATRIX have to be the wavelength solutions for the fibre for which the drift is computed, fibre A in this example.

```
/data/cal/ESPRESSO_1x1_CCD_geom_config.fits CCD_GEOM
```

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/data/cal/ESPRESSO_SINGLEHR_1x1_master_inst_config_2018-10-14.fits MASTER_INST_CONFIG

/data/reduced/2019-06-24/r.ESPRE.2019-06-25T12:26:36.874_WAVE_MATRIX_THAR_FP_A.fits WAVE_MATRIX
/data/reduced/2019-06-24/r.ESPRE.2019-06-25T12:26:36.874_DLL_MATRIX_THAR_FP_A.fits DLL_MATRIX

/data/reduced/2019-06-24/r.ESPRE.2019-06-25T12:20:17.239_S2D_BLAZE_FP_FP_A.fits S2D_BLAZE_FP_FP_A
/data/reduced/2019-06-24/r.ESPRE.2019-06-25T12:36:03.728_S2D_BLAZE_FP_FP_A.fits S2D_BLAZE_FP_FP_A
/data/reduced/2019-06-24/r.ESPRE.2019-06-25T14:53:17.094_S2D_BLAZE_FP_FP_A.fits S2D_BLAZE_FP_FP_A
/data/reduced/2019-06-26/r.ESPRE.2019-06-26T17:02:01.813_S2D_BLAZE_FP_FP_A.fits S2D_BLAZE_FP_FP_A
/data/reduced/2019-06-27/r.ESPRE.2019-06-27T17:33:03.243_S2D_BLAZE_FP_FP_A.fits S2D_BLAZE_FP_FP_A
/data/reduced/2019-06-27/r.ESPRE.2019-06-27T18:09:53.007_S2D_BLAZE_FP_FP_A.fits S2D_BLAZE_FP_FP_A
/data/reduced/2019-06-27/r.ESPRE.2019-06-28T11:09:24.917_S2D_BLAZE_FP_FP_A.fits S2D_BLAZE_FP_FP_A
/data/reduced/2019-06-28/r.ESPRE.2019-06-28T19:12:16.051_S2D_BLAZE_FP_FP_A.fits S2D_BLAZE_FP_FP_A
/data/reduced/2019-06-28/r.ESPRE.2019-06-28T19:28:04.485_S2D_BLAZE_FP_FP_A.fits S2D_BLAZE_FP_FP_A
/data/reduced/2019-06-28/r.ESPRE.2019-06-29T11:03:26.043_S2D_BLAZE_FP_FP_A.fits S2D_BLAZE_FP_FP_A

And here is an example of the esorex command to launch the recipe:

```
esorex -output-dir=/data/reduced/DRIFT espdr_compu_drift drift_input_HR11_FP_FP_A.sof
```

9.13 espdr_wave_THAR_THAR

The espdr_wave_THAR_THAR recipe is not part of the reduction cascade. It allows to get the de-flatted and de-flatted-de-blazed S2D extracted spectra. Mainly used to reduce THAR-THAR or UN-UN frames. It can be launched by hand, e.g. with esorex.

9.13.1 Input

type	TAG	n	setting
raw	THAR_THAR	1	any
ref	CCD_GEOM	1	match
ref	INST_CONFIG	1	match
ref	ORDERS_MASK	1	match
cdb	HOT_PIXEL_MASK	1	match
cdb	MASTER_DARK	1	match
cdb	BAD_PIXEL_MASK	1	match
cdb	ORDER_TABLE_A	1	match
cdb	ORDER_TABLE_B	1	match
cdb	ORDER_PROFILE_A	1	match
cdb	ORDER_PROFILE_B	1	match
cdb	FSPECTRUM_A	1	match
cdb	FSPECTRUM_B	1	match
cdb	BLAZE_A	1	match
cdb	BLAZE_B	1	match

9.13.2 Output

ID	PRO.CATG	type	Note
0	S2D_THAR_THAR_A	cdb	S2D Extracted spectrum for fibre A
1	S2D_THAR_THAR_B	cdb	S2D Extracted spectrum for fibre B
2	S2D_BLAZE_THAR_THAR_A	cdb	S2D Extracted blaze for fibre A

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3	S2D_BLAZE_THAR_THAR_B	cdb	S2D Extracted blaze for fibre B
---	-----------------------	-----	---------------------------------

9.13.3 Quality control

NONE

9.13.4 Parameters

NONE

9.14 espdr_wave_LFC_LFC

The espdr_wave_LFC_LFC recipe is not part of the reduction cascade. It allows to get the de-flatted and de-flatted-de-blazed S2D extracted spectra. Mainly used to reduce LFC-LFC frames. It can be launched by hand, e.g. with esorex.

9.14.1 Input

type	TAG	n	setting
raw	LFC_LFC	1	any
ref	CCD_GEOM	1	match
ref	INST_CONFIG	1	match
ref	ORDERS_MASK	1	match
cdb	HOT_PIXEL_MASK	1	match
cdb	MASTER_DARK	1	match
cdb	BAD_PIXEL_MASK	1	match
cdb	ORDER_TABLE_A	1	match
cdb	ORDER_TABLE_B	1	match
cdb	ORDER_PROFILE_A	1	match
cdb	ORDER_PROFILE_B	1	match
cdb	FSPECTRUM_A	1	match
cdb	FSPECTRUM_B	1	match
cdb	BLAZE_A	1	match
cdb	BLAZE_B	1	match

9.14.2 Output

ID	PRO.CATG	type	Note
0	S2D_LFC_LFC_A	cdb	S2D Extracted spectrum for fibre A
1	S2D_LFC_LFC_B	cdb	S2D Extracted spectrum for fibre B
2	S2D_BLAZE_LFC_LFC_A	cdb	S2D Extracted blaze for fibre A
3	S2D_BLAZE_LFC_LFC_B	cdb	S2D Extracted blaze for fibre B

9.14.3 Quality control

This recipe computes the following QC parameters (on the image extension n, order m, and read-out region i,j):

QC key name	description
-------------	-------------

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QC EXTn ROXi ROYj MAX FLUX	max flux on raw image [ADU]
QC ORDERm COSMIC NB	number of cosmics detected in order m
QC SATURATION CHECK	quality check on saturation
QC COSMIC NB	number of cosmics
QC LFC WAVE CHECK	overall quality check

9.14.4 Parameters

NONE

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10 Quick start

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

10.1 NIRPS pipeline recipes

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

`espdr_mdark` Creates the master dark & hot pixel mask;
`espdr_led_ff` Computes the mean gain per detector and detect the bad pixels;
`espdr_orderdef` Characterises the orders as imaged on the CCD;
`espdr_mflat` Creates the master flat, blaze and order profiles;
`espdr_wave_FP` Wavelength calibration with FP;
`espdr_wave_THAR` Wavelength calibration with THAR and FP;
`espdr_wave_LFC` Wavelength calibration with LFC and FP;
`espdr_cal_contam` Generates a contamination frame and checks contamination level on science fibre;
`espdr_cal_eff_ab` Computes the relative efficiency between sky and science fibres vs. wavelength;
`espdr_cal_flux` Measures the absolute efficiency curve;
`espdr_sci_red` Performs science reduction;

Other three stand-alone recipes are also provided:

`espdr_compu_drift` Measures instrumental drift on wavelength calibration spectra
`espdr_wave_THAR_THAR` S2D extraction of THAR, THAR frames
`espdr_wave_LFC_LFC` S2D extraction of LFC, LFC frames

10.2 An introduction to EsoRex

Before being able to call pipeline recipes to process a set of data, the data must be correctly classified, and associated with the appropriate calibrations. The *Data Classification* consists of tasks such as: "What kind of data am I?", e.g., DARK, "to which group do I belong?", e.g., to a particular set of data that needs to be processed together. *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. Since all the required information is stored in the FITS headers, data association is based on a set of header keywords (called "association keywords") and the process 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, namely:

- *EsoRex* is a command line tool used to run each pipeline recipe. *EsoRex* commands can be easily scripted.
- The La Silla observatory implements automatic data management tools that trigger the execution of pipeline recipes. This aspect is not covered in this manual.

10.2.1 Using EsoRex

EsoRex is a command line utility for running pipeline recipes. Users may embed *EsoRex* into data reduction scripts. However, with *EsoRex* users must manually classify and associate the data using the information contained in the FITS header keywords (see Section 6, page 19). The user has to define the input set-of-frames (SOF) and potentially set configuration parameters.

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The set-of-frames: Each pipeline recipe is executed for a set of input FITS data files. When using *EsoRex* the filenames must be listed together with their Data Organiser (DO) category ¹¹ in an ASCII file, the *set-of-frames* (SOF), that is required when launching a recipe. A Set Of Frames (SOF) is a an ASCII text file that lists each input frame(full path), specifying its DO category. Here is an example of SOF, valid for the *espdr_orderdef* recipe

```
/file_path/NIRPS_HA_ORDERDEF089_0001.fits ORDERDEF_A
/file_path/NIRPS_HA_ORDERDEF089_0002.fits ORDERDEF_B

/file_path/NIRPS_CCD_geom_config.fits CCD_GEOM
/file_path/NIRPS_HA_master_inst_config.fits MASTER_INST_CONFIG
/file_path/NIRPS_hot_pixels.fits HOT_PIXEL_MASK
/file_path/NIRPS_master_dark.fits MASTER_DARK
/file_path/NIRPS_bad_pixels.fits BAD_PIXEL_MASK
```

Note that the NIRPS 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 *espdr_orderdef* will treat the frame `/file_path/NIRPS_HA_ORDERDEF089_0001.fits` as a `ORDERDEF_A`, the frame `/file_path/NIRPS_hot_pixels.fits` as a `HOT_PIXEL_MASK`, 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 instrument mode, and detector bin setting, and that the appropriate calibration files have been specified.

EsoRex syntax: `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 file: Each pipeline recipe can be controlled by specifying its configuration parameters. One way is to define them on command line. Alternatively parameters can be defined through a recipe configuration file. This is an ASCII file listing parameters, their values and their description. Each pipeline recipe may be assigned an *EsoRex* configuration file, containing the default values of the parameters related to that recipe. Recipe configuration files are normally (by default) 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 *espdr_sci_red* has its *EsoRex* generated configuration file named `espdr_sci_red.rc`, and is generated with the command:

esorex - -create-config espdr_sci_red

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

```
# --rv_center
# Approximate RV.
espdr.espdr_sci_red.rv_center=0.0
```

In this example, the parameter `espdr.espdr_sci_red.rv_center` is set to the value `0.0`. In the configuration file generated by *EsoRex*, one or more comment lines describing the parameter purpose are added, and an alias that could be used as a command line option.

The recipes provided by the ESPRESSO 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

¹¹The indicated *Data Organizer 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*

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the instrument name but also the name of the recipe 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**¹².

A recipe configuration file different from the default one can be specified on the command line:

esorex - --recipe-config=my_alternative_recipe_config

The reader can find a complete description of all recipe parameters in section 9. Their purpose is described in Section 11.

For a configuration file to be used as configuration file, the file should be explicitly defined with the syntax above.

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 *espdr_sci_red* for processing the files specified in the set-of-frames *espdr_sci_red.sof*:

esorex espdr_sci_red espdr_sci_red.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 *espdr_sci_red* recipe *rv_center* parameter to 3.0, the following should be typed:

esorex espdr_sci_red --rv_center=3.0 espdr_sci_red.sof

For more information on *EsoRex*, see www.eso.org/cpl/esorex.html.

¹²If 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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11 Algorithms and recipe details

In this section we describe the main algorithms implemented in the NIRPS pipeline recipes. Relevant data reduction parameters are typed in **bold** face. The full name of the parameter **dark_ksigma** of the recipe `espdr_mdark` is actually `espdr.espdr_mdark.dark_ksigma`. For convenience we omit the common prefix `espdr.espdr_mdark.` for parameter description, the common prefix `espdr_` for the recipe description as well as the step prefix name for the algorithm description.

11.1 Algorithms

11.1.1 Master frame combination using a kappa-sigma-clipped mean/median

A kappa-sigma-clipped mean or median may be used on a per-pixel basis to combine a set of frames into a master frame, thereby excluding outlier pixel values, i.e. the cosmics. In this technique, the median gives more accurate results. The user may set the method (**sig_clip_method**): mean or median, and the kappa value (**ksigma**) controlling thresholds used to clip outliers. This algorithm is used in all recipes that do frame stacking: `mdark`, `led-ff` and `mflat`.

11.1.2 Non-linearity correction

All the frames are already corrected for the non-linearity during the construction of the raw frame from individual reads. However, for more security a correction is also done via the application of the bad-pixel mask. The bad-pixel mask is derived from frames uniformly illuminated with the LED source, installed inside of the cryostat. The pixels marked as bad in the mask are not considered in the extraction of the S2D spectra.

11.1.3 Persistence

Persistence corresponds to a signal from a science frame that survives past the reset of the detector. It is particularly problematic when one observes a bright star followed by a much fainter star of a similar spectral type. The spectrum of the first star is superposed onto the spectrum of the second star, leading to a velocity bias.

To reduce persistence, we propose the flash-flooding of the science array. Following the bright flat field, the array is saturated with the internal LED. The idea being to replace the persistence from the spectral trace with a known persistence from the LED.

At a $3e-5$ fractional persistence (6 minutes with flash-flooding, 10 minutes without), a contaminating star that is offset by 4 km/s in RV would inject an RV offset in the contaminated object at the level of 0.12 m/s times the flux ratio. To remain below an RV effect below 1 m/s, consecutive targets should have magnitude differences of less than 2.3 mags.

11.1.4 Order definition

Orders are identified on ORDERDEF frames through a clumping algorithm that groups together neighbouring pixels whose values exceed the computed background. The algorithm acts recursively on all pixels meeting the flux criterion, within a given distance, until all pixels have been classified either as belonging to a clump or as background.

Clumps are then screened against several criteria to establish whether they represent valid orders: minimum length in main dispersion direction and minimum width in cross-dispersion direction. The clumps that do not meet the criteria are discarded.

After that, orders are assigned physical interference orders. This numbering is established by using input parameters specifying the physical number of the first detected order and the number of valid orders to be found.

Finally, order shapes and positions in cross-dispersion direction are fitted at several locations along the main dispersion using a Gaussian model. Note that the Gaussian fit is only needed to approximately measure order center. Then, a low-order polynomial is fitted to the Y position of each order as a function of X, where X is the main dispersion direction and Y is the cross-dispersion direction. Only the center of the order in Y is relevant at this stage, not their shape in the Y direction. The only purpose of these polynomials is to

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provide order center vs. X position to 0.5 pixel precision in order to define the window of extraction that will be used by the subsequent spectrum extraction procedure.

11.1.5 Background subtraction

The strategy to measure the diffuse background light on the detector is the following:

- Divide the detector into a grid of small regions (100x100 pixels in size)
- In each region, excluding the pixels belonging to spectral orders, build an histogram of (background) pixel values.
- Estimate the mode of the pixel value distribution by fitting a second-order polynomial to the histogram bins closest to the peak of the distribution. The mode of the distribution is taken as the best approximation of the local background level.
- Interpolate the background levels measured in each region over the whole detector using cubic splines. These cubic splines have low order or few nodes, i.e., are smoothly varying over the detector.

A background map is then generated and subtracted from the raw frame.

11.1.6 Spectrum Extraction

As of today, all major fiber-fed spectrographs designed for precise radial velocity work produce relatively symmetric, round slit images on the detector (e.g. ELODIE, CORALIE, HARPS, SOPHIE). This results from the use of circular fibres and simple light injection with no image or pupil slicing at spectrograph entrance. Moreover, the curvature of echelle orders on the detector is generally small. The dispersion direction is constant and along the lines, or, in other words, the slit tilt is zero accross the wavelength range. In this case, spectrum extraction can be made by simply summing the flux in cross-dispersion direction, parallel to the CCD rows/columns. The resulting S2D spectrum is sampled on the grid of extracted pixels. Note that this extraction process has the advantage of avoiding any resampling procedure.

Two spectrum extraction functions are provided in the NIRPS DRL, same as for ESPRESSO: simple summation, and optimal extraction following the well-known Horne method (Horne 1986, PASP 98, 609). We investigated refinements introduced by e.g. Marsh (1989) and Donati et al. (1997), but they are generally not relevant in the case of NIRPS. The maximum tilt of the HE rectangular slit is +- 5 degrees on the edge of the reddest spectral orders, such a tilt will introduce locally a resolution degradation of 6% at maximum. We considered that a tilted extraction, mandatory only for the extreme of the reddest spectral orders of the HE mode, is not justified and could introduce one additional parameter of instability. Nevertheless, the Horne optimal extraction algorithm has been modified significantly and optimised for ESPRESSO, and taken for NIRPS, in the following ways:

- Order profiles in cross-dispersion direction are obtained directly from spectral flat-field exposures at high SNR, which serve as empirical models. Such exposures are part of the standard calibration sets and must be obtained within 24 hours of science observations. We make use here of the high stability of ESPRESSO which guarantees that the position and shape of spectral orders remain essentially constant between calibrations and science exposures. NIRPS is as stable as ESPRESSO for the orders position and shape - the internal drift below 1 millipixel over 1 night was demonstrated in lab - therefore the same strategy can apply.
- For exposures taken with simultaneous reference on fiber B (UNe/LFC/FP), a *contamination frame* can be used as additional empirical model in the optimal extraction. This means that the spectrum is modelled as the sum of a scaled order profile and a scaled contamination profile. The obtained science flux is therefore corrected from direct UNe/LFC/FP contamination. As for the *usual* optimal extraction, the model is linear in both model parameters (science and contamination fluxes), and the solution is thus obtained by analytically solving the associated linear least-squares problem.

11.1.7 Flat-Fielding

The extraction procedure described above delivers a spectrum that is still affected by variable pixel-to-pixel sensitivity along the main dispersion direction. To correct for that, the spectrum is divided by the normalised extracted flat-field, obtained from co-added FLAT frames and extracted in exactly the same way as the science spectrum.

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We note that this flat-fielding procedure will remove not only pixel-to-pixel sensitivity variations, but also fringing effects, at least when the science spectrum is broadly similar to the one of the flat-field lamp. This is the case for all stellar spectra at moderate to high SNR. In the case of a very low SNR spectrum dominated by sky emission lines, the correction of fringing may in principle be less accurate. However, fringing by sky lines is expected to be a very small effect at the high spectral resolution of NIRPS. The calibration images of NIRPS reveal no fringing at all.

11.1.8 Wavelength Calibration

There are two methods used for the wavelength calibration, according to the calibration source used: ThAr lamp together with Fabry-Perot, or Laser Frequency Comb.

UNe and Fabry-Perot Lamps

First the FP peaks are identified on the frame with both fibres illuminated with the Fabry-Perot lamp. Then the tables of these peaks are passed to the reduction of the frames in which one of the fibres is illuminated with the UNe lamp, while the other fibre has the Fabry-Perot light for the drift calculation. Combining the detected FP peaks and the carefully chosen UNe lines with precise wavelengths assigned, allows to compute the precise wavelength solution per extracted order. The wavelength solution fit is done on the detected Fabry-Perot peaks, which are anchored to the precise wavelength through the known UNe lines.

UNe spectra are characterised by a high density of emission lines with many blends and very different intensities. Identifying and properly fitting all these lines is a challenging task, especially when aiming at a repeatability of better than 1 m/s in the wavelength calibration. Variable line intensities make it necessary to use a static UNe table to initiate the wavelength calibration process. This table indicates the approximate position of lines. Each NIRPS mode has its own UNe lines table.

UNe lamps evolve with time, and the ageing process has several consequences on their spectra. Both line intensities and wavelengths are affected. To mitigate this, a line-by-line comparison with the static UNe table is performed to identify and reject individual lines potentially affected by fitting instabilities. More explicitly, this is the relative intensity change of Neon lines versus Uranium lines which may affect the apparent position of blended lines. Fortunately there is less Neon lines in the UNe spectra than Argon lines on the ThAr Spectra.

Laser Frequency Comb

Given the previously computed wavelength solution, the Laser Frequency Comb allows to achieve a more stable and precise solution. No static table is needed to initiate the wavelength calibration process, since emission LFC lines can be searched and identified automatically thanks to the absolute accuracy of the comb pattern. Then, the wavelength of each peak is determined. To do this, the DRL first computes a list of theoretical LFC wavelengths based on the known repetition rate and anchor frequency of the LFC. Then, these wavelengths are assigned to individual peaks by comparison with a previously-obtained UNe wavelength calibration, which provides a suitable first guess for the wavelength of the LFC lines. Possibly the LFC will not cover the whole spectral range, the orders with insufficient number of detected LFC lines (less than the limit fixed in the instrument configuration) have to take the solution from the UNe method. Also, the orders, for which the LFC solution has the RMS or the CHI2 higher than limits fixed in the instrument configuration, have the UNe wavelength solution assigned. The FITS header keywords indicate for each order where the wavelength solution is coming from.

11.1.9 Instrumental Drift Measurement

The simultaneous reference fibre of NIRPS is used either for sky subtraction or instrumental drift correction. Instrumental drift is measured using wavelength calibration sources, either the stabilised Fabry-Perot etalon (FP) / UNe or the LFC. Drift is measured by comparing two similar S2D spectra on the simultaneous reference fibre: one that is acquired at the time of the wavelength calibration (with both fibre A and fibre B illuminated by a calibrator), and one that is acquired simultaneously with the science observation. The algorithm used by the pipeline to compute the drift is based on the method described in Connes (1985), ApSS 110, 211, and Bouchy et al. (2001), A&A 374, 733. The drift is simply obtained from a first-order Taylor expansion of the spectrum at each individual pixel, i.e. the measured flux difference between the two spectra at pixel X is converted into a position difference using the measured spectrum derivative at pixel X. This obviously assumes that the spectrum derivative is constant over a length X that is the shift between the two spectra. Therefore, this method only works for drifts that are small relative to the FWHM of the spectral lines, i.e. typically smaller than one pixel. The pixel size in NIRPS is equal to 1 km/s, while the expected instrumental drifts are smaller than 1 m/s over 24 hours. The method described here is thus applicable for corrections in between daily wavelength calibrations. It has the significant advantage that

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no modelling of the spectrum is needed to measure the drift, since each individual pixel independently contributes to the total drift. Note that pixels are weighted according to their Doppler information content, which is proportional to the square of the spectrum derivative.

This algorithm has been successfully used on HARPS to measure drifts of ThAr spectra. For ESPRESSO a few improvements were made to the method to adapt it to LFC/FP spectra and make it more robust in general. The following aspects are addressed:

- Flux normalisation: the method only works if the two spectra are normalised to the same flux level. Thus a global flux normalisation on the S2D spectrum is performed.
- Local vs. global drift measurement: instrumental drifts may vary across the spectral format, i.e. a single, global value for the drift may be too coarse an approximation. It is possible to specify to the algorithm whether the drift computation and correction should be global, chip-by-chip or order-by-order.

With the algorithm described here, the instrumental drifts can be reliably measured to a precision of 1-2 cm/s globally (if not limited by photon noise).

11.1.10 Sky Subtraction

Sky subtraction in NIRPS can be made by observing in simultaneous sky mode and subtracting the sky spectrum obtained on fibre B from the science spectrum on fibre A. In practice, this process involves several steps:

- Measure the relative throughput of fibre B with respect to fibre A as a function of wavelength (in S2D format) by acquiring EFF_AB exposures, which are obtained by pointing the telescope at daylight sky. Note that the sky fills the entire fibre aperture uniformly, so that pointing/guiding errors or telescope pointing jitter have no effect on the amount of sky flux entering the spectrograph.
- Scale the S2D simultaneous sky spectrum using the previously-obtained relative efficiency curve.
- Rebin the scaled S2D sky spectrum to the same wavelength scale as fibre A. The resampling is done by spline interpolation of the cumulative flux vs. extracted pixel, ensuring flux conservation. Note that the wavelength scales of fibres A and B are extremely similar, so that the resampling will essentially consist of a small shift of the spectrum that is slowly varying along spectral orders.
- Subtract the scaled and rebinned S2D simultaneous sky spectrum from the S2D science spectrum.

For NIRPS two sky subtraction methods are available: *pixel-by-pixel* and *smoothed*. The first method subtracts the sky spectrum on a pixel-by-pixel basis. The second one performs first a sliding average of the sky spectrum and then subtracts it from the science spectrum. For very low S/N regime, readout limited or close to it, it is recommended to use the option smooth, thus reducing the readout noise contribution from the step of sky subtraction.

The precision of sky subtraction with NIRPS is essentially photon- and readout-noise limited, provided the sky fibre *sees* the same sky as the science fibre.

11.1.11 Barycentric Correction

In the context of high-resolution astronomical spectroscopy and high-precision radial velocity measurements, it is necessary to compute to high accuracy the projection of the velocity vector of an Earth-bound observer along the line of sight to an astronomical target, at the time of the observation, as measured within the ICRS reference frame (centred on and at rest with respect to the Solar System barycenter). The computation should take into account both the Earth's orbital motion around the Sun and the observer's motion due to Earth rotation. A new code for this computation was developed for ESPRESSO and used for NIRPS, based on recent Solar System ephemerides produced at Institut de Mécanique Céleste et de Calcul des Ephémérides (IMCCE) in Paris.

The algorithm:

- Computes the observer's projected velocity in the direction of the target in the ICRS reference frame at the time of the observation with the accuracy of at least 1 cm/s.

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- Computes the barycentric time of light arrival, i.e. the time at which the light from the target reaches the Solar System barycenter given its detection by the Earth-bound observer at the time of the observation with the accuracy of at least 1s.
- Computes an upper bound to the maximum value of the barycentric correction over one year for any given target.

Input parameters:

- Right ascension of target in decimal hours, ICRS system, epoch 2000.0
- Declination of target in decimal degrees, ICRS system, epoch 2000.0
- Proper motion of target in right ascension ($\mu_{\alpha} \cos \delta$) in arcsec/year, ICRS system
- Proper motion of target in declination in arcsec/year, ICRS system
- Date of observation in UTC (year, month, day, decimal hour)
- Longitude of observer in decimal degrees
- Latitude of observer in decimal degrees
- Altitude of observer above sea level in km

Output parameters:

- Velocity component of observer projected onto target line of sight in km/s, ICRS system (abridged as BERV for Barycentric Earth Radial Velocity)
- Total velocity of observer in km/s, ICRS system
- Barycentric time of light arrival as TDB Julian date
- Yearly maximum value of BERV (upper bound)

Step-by-step description:

- Compute Julian date from given date and time of observation
- Compute ICRS target coordinates at the time of observation (i.e. take proper motion into account)
- Compute observer's velocity vector with respect to geocenter at the time of observation, ICRS system (correct for precession and nutation)
- Compute Earth's orbital velocity vector at the time of observation, ICRS system
- Combine rotational and orbital motion into total velocity vector
- Project velocity vector onto target line of sight to obtain BERV
- Compute barycentric time of light arrival
- Compute yearly upper bound to BERV

11.1.12 Order Rebinning and Merging

The rebinning and merging process to create a S1D spectrum from the S2D spectrum is as follows:

- Define a uniform wavelength grid with a constant wavelength step that is close to the average pixel size in wavelength units.
- For each spectral order, build the cumulative flux distribution vs. extracted pixel.
- Interpolate the cumulative flux function onto the uniform wavelength grid using cubic splines.
- Build the resampled spectrum by differentiating the interpolated cumulative flux.
- Merge resampled spectral orders, computing the weighted average of rebinned pixels where spectral orders overlap.

This technique is chosen because it conserves the integrated flux within any two wavelengths of the original pixel grid. Moreover, cubic splines are well suited to ESPRESSO spectra because of the well-sampled PSF of the instrument (4 pixels FWHM in singleHR mode), which ensures that the spectrum derivatives can be numerically estimated in a reliable way.

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11.1.13 Radial Velocity Computation

The NIRPS DRL implements a cross-correlation module that computes the cross-correlation function (CCF) of a S2D spectrum with respect to a binary template (mask) of a given spectral type. The radial velocity (RV) is then obtained from a Gaussian fit to the CCF. This technique has been successfully used on the ELODIE, CORALIE, HARPS, SOPHIE, HARPS-N and ESPRESSO spectrographs (see Baranne et al. 1996, A&AS 119, 373, and Pepe et al. 2002, A&A 388, 632). One of its main advantages is that CCFs can be computed in an automatic way using a line mask. Line masks are simply lists of central wavelengths and depths of spectral lines, and can be created for various spectral types. We note here that the CCFs of slowly-rotating stars are extremely well approximated by Gaussian profiles with a flat continuum. However, the particular fitting function does not matter much; the crucial aspect is to fit the CCFs of a given star with always the same function to avoid systematic effects on the derived radial velocities. As such, it is fundamental to reduce all the spectra with the same mask and CCF parameters, as comparison between reductions with different parameters will be affected by systematics.

The main steps of the algorithm are:

- Compare the global flux distribution in the S2D spectrum to a static flux template that approximately corresponds to the spectral type of the star. The S2D flux is scaled accordingly to match the flux distribution of the template. In this way, spectra of any given star are always brought to the same flux distribution, which ensures that variable atmospheric conditions will not induce systematic effects in the CCF computation.
- Shift the wavelength scale of the S2D spectrum to the Solar System barycenter using the barycentric correction.
- Define a uniform radial velocity grid that is approximately centered on the radial velocity of the star.
- For a given RV value in the grid, shift the line mask by the corresponding Doppler shift, project the line mask onto the S2D spectrum using a specified line width (about one pixel), and sum the S2D flux that goes through the so-defined mask *holes*. The flux from partial pixels is computed via simple linear interpolation. The sum is actually a weighted sum, using line depths as weights to optimally extract the Doppler information. During this process, the S2D spectrum is locally blaze-corrected to remove any continuum slope around spectral lines. This produces one point of the CCF.
- Loop over all RV values in the grid.
- Fit a Gaussian profile to the CCF to derive RV, FWHM and contrast.

Note that, by construction, CCFs are simply co-added spectral lines in velocity space, weighted by their depth and continuum flux and corrected of the transmission of the grating (blaze function). As such they can be considered as a *master* spectral line for the star.

11.1.14 Removal of cosmic rays

Cosmic rays are identified via a ksigma rejection when extracting the one-dimensional spectrum of one order. In each recipe that does it, the clipping is regulated by a dedicated parameter. In the science recipe, `espr_sci_red` the clipping is regulated by the parameter `ksigma_cosmic`. A value of -1 turns off the ksigma clipping.

The science recipe has also an additional algorithm to detect cosmic rays, that exploits LACosmic (van Dokkum 2001, PASP, 113, 1420). The algorithm is applied to the so-called detector cleaned frames, i.e. the raw science where the overscan regions have been trimmed and their contribution subtracted. Cosmics identified this way are masked during the extraction of the one-dimensional spectra.

Both algorithms can be run simultaneously.

The LA Cosmic algorithm is regulated by the following parameters: `cosmic_detection_sw`.

- `cosmic_detection_sw`. It turns LA Cosmic on (1) or off (0). By default, its value is taken by the input instrument configuration table. The algorithm is turned on for SKY-mode and it is turned off for FP mode observations.
- `lacosmic.post-filter-mode` : dilage/dilute. It specifies whether cosmic ray mask has to be dilated (i.e. expanded) or diluted (i.e. shrunk). It takes effect only if the post-filter-x/y values are positive.
- `lacosmic.post-filter-x` : X Size of the post filtering kernel. The mask is dilated or diluted by this amount along x direction. Default: 0.

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- **lacosmic.post-filter-y** : Y Size of the post filtering kernel. The mask is dilated or diluted by this amount along y direction. Default: 0.
- **lacosmic.sigma_lim** : LA Cosmic Poisson fluctuation threshold. It is the minimum value of the fluctuation image, obtained by dividing the Laplacian image (a second order derivative of the original image along x and y) and the noise model. High values of **sigma_lim** find the more intense cosmics and have less risk to detect false positives. Low values are more efficient in finding also faint cosmics, but have higher risk to detect false positives.
The default values are taken by the input instrument configuration table: 5 (SHR-SKY, 2x1), 7 (SHR-FP, 2x1), 7 (SHR 4x2), 8 (SUHR 1x1), 10 (MHR 4x2), 8 (MHR 8x6).
- **lacosmic.f_lim** : LA Cosmic minimum contrast between the Laplacian image (see above) and the fine-structure image (created from the original image by a combination of median filters). High values of **f_lim** find the more intense cosmics and have less risk to detect false positives. Low values are more efficient in finding also faint cosmics, but have higher risk to detect false positives.
The default values are taken by the input instrument configuration table: 5 (SHR-SKY, 2x1), 5 (SHR-FP, 2x1), 5 (SHR 4x2), 8 (SUHR 1x1), 4 (MHR 4x2), 5 (MHR 8x6).
- **lacosmic.max_iter** : LA Cosmic max number of iterations. [5]
- **extra_products_sw** : Set to TRUE to create extra products to inspect LA Cosmic results. [FALSE]

11.1.15 Error and Bad Pixel Propagation

S2D Spectra

All significant error sources are propagated through the pipeline using the standard error propagation formulae. We list below the noise sources that are taken into account in the science reduction cascade producing the S2D spectra:

- Detector readout noise, which for a large number of reads converges towards 6e-
- Detector dark current noise
- Total photon noise on science fiber (science target + diffuse background)
- Flat-fielding noise (should be less than 1%)
- Sky noise if applicable (simultaneous sky mode)

Error propagation for S2D spectra is relatively straightforward since there is no resampling step in the process. Extracted pixels remain independent of each other.

If not too many, bad pixels and hot pixels will be ignored during the spectrum extraction process. The presence of bad/hot pixels will be reported in the quality maps associated to science products; they are therefore traceable throughout the reduction chain.

S1D Spectra

The resampling process that is necessary to generate S1D spectra from S2D spectra inevitably introduces correlations between adjacent rebinned pixels in the S1D spectra. To calculate the errors on the S1D spectra one propagates errors in the usual way to the S1D spectrum, while including in the error computation an additional array containing the correlation factor of each rebinned pixel. This factor is the quadratic sum of the relative contributions of the original pixels to the rebinned pixel, considering that a maximum of two original pixels contribute to the rebinned pixel. In this way we believe all the information on noise properties is conveyed into the S1D spectrum. We note however that the existence of correlations makes the use of the S1D spectrum non-trivial for science purposes if a rigorous treatment of the noise is required. It is up to the user to understand how to deal with this issue, e.g. when performing least-squares fitting of models to the S1D spectrum.

In general, the use of the S2D spectrum is recommended whenever possible to avoid correlations between adjacent data points, which are unavoidable as soon as some resampling is performed.

Cross-Correlation Functions

Uncertainties on the CCF data points are obtained by propagation of S2D error maps through the cross-correlation stage, which is a simple additive process (fluxes from many spectral lines are co-added). Finally, an estimate of the radial velocity uncertainty is obtained by converting CCF flux errors into RV errors using the measured CCF derivative, as described in Boisse et al. (2010), A&A 523, 88 (appendix).

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11.2 Recipes

An overview of the data reduction cascade is given in Section 8.

11.2.1 mdark

The recipe creates a master dark frame from a set of minimum five dark frames. All the input raw frames are stacked and a sigma-clipping algorithm is applied to remove the cosemics. The cosemics rates are saved in the FITS header as QC KWs. The hot pixels are detected via the sigma-clipping algorithm and saved in the hot_pixels frame. Their number per detector output is saved in the FITS header as QC KW. The mean dark current is computed for each detector output and saved in the FITS header as QC KW.

11.2.2 led_ff

The recipe detects the bad pixels and computes the conversion factor for each detector output. For this at least two sets with different exposure times of minimum five frames each are needed. The frames are the images of the detector fully illuminated by a LED. The recipe first removes the bias and the dark current and then stacks the frames with the same exposure time. The cosemics are removed via the sigma-clipping algorithm. The bad pixels are detected via checking of the linearity of their behaviour with respect to the exposure time. Their number is saved in the FITS header as QC KW. The conversion factor is computed within a window defined for each detector output and saved in the FITS header as QC KW. The raw frames are checked against the saturation and the corresponding QC KW is set. The same is done for the minimal flux. The computed conversion factor is checked against the theoretical value taken from the FITS header of the raw frame.

11.2.3 orderdef

The recipe detects the orders position in the image. The input frames are two flat images: one for fibre A and one for fibre B. Each input raw frame is checked for the saturation and cleaned from the dark current via the scaled MASTER_DARK subtraction. A FITS keyword QC CHECK is added and set to 1 in case of correct and 0 for bad quality results. Then the orders detection is performed:

- For each pixel, decide if it belongs to an order or to the background.
- Run the clumps detection algorithm, which marks the pixels belonging to the same clump.
- Detect which of the clumps are valid orders.
- Attribute interference / physical order numbers.
- Fit the valid orders position.
- Mark the orders position on the ORDER_TABLE products.
- Save the coefficients of the fit in the 2nd extension of the ORDER_TABLE products.

11.2.4 mflat

The recipe generates the extracted flat-field, blaze function and the order profile. Recipe steps:

- Check the raw frame for saturation.
- Remove the dark current via the scaled MASTER_DARK subtraction
- Measure and subtract inter-order background.
- Perform optimal extraction of orders for both fibres.
- Compute the blaze function.
- Correct the blaze function for spectral energy distribution of the source and instrumental efficiency by fitting the flux distribution at blaze peak.

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- Save the QC KWs in the FITS header of the products: max flux per detector output, background min, max and mean per extension (blue and red), number of removed cosmics per order, SNR per order, RMS of the flat per order, QC CHECKS
- Save the ORDER_PROFILE, the FLAT and the BLAZE for each fibre

11.2.5 cal_contam

The recipe generates a contamination frame and checks the contamination level on science fibre. Recipe steps:

- Check the raw frame for saturation.
- Remove the dark current via the scaled MASTER_DARK subtraction
- Measure and subtract inter-order background.
- Perform optimal extraction of orders for both fibres.
- Correct the flat-field.
- Measure the maximum contamination level in extracted spectrum and compare it with the specified threshold.
- Save the contamination frame with QC KWs.

11.2.6 cal_eff_ab

The recipe computes the relative efficiency between sky and science fibres vs. wavelength. Recipe steps:

- Check the raw frame for saturation.
- Remove the dark current via the scaled MASTER_DARK subtraction
- Measure and subtract inter-order background.
- Perform optimal extraction of orders for both fibres.
- Correct the flat-field.
- Divide reference spectrum by science spectrum and fit a low-order polynomial across each order.
- Save the relative efficiency frame with QC KWs.

11.2.7 wave_FP

Recipe detects the Fabry-Perot peaks. Recipe steps:

- Check the raw frame for saturation.
- Remove the dark current via the scaled MASTER_DARK subtraction
- Perform optimal extraction of orders for both fibres.
- Correct the flat-field and the blaze.
- Search for the FP lines.
- Fit the FP lines.
- Check if there are no lines missing.
- Save the FP lines table and S2D, S2D_BLAZE products with QC KWs.

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11.2.8 wave_THAR

Recipe performs the wavelength calibration using the UNe lamp and Fabry-Perot spectra. Recipe steps:

- Remove the dark current via the scaled MASTER_DARK subtraction
- Perform optimal extraction of orders for both fibres.
- Correct the flat-field and the blaze.
- Fit the UNe lines provided in a static table.
- Measure drift and apply it to the FP lines table (product of the wave_FP recipe).
- Check if there are no FP lines missing.
- Compute the wavelength for all the FP lines, using UNe lines.
- Fit D lambda.
- Fit the wavelength solution.
- Fit the UNe raw lines.
- Save the products with QC KWs.

11.2.9 wave_LFC

Recipe performs the wavelength calibration using the Laser Frequency Comb spectrum. Recipe steps:

- Remove the dark current via the scaled MASTER_DARK subtraction
- Perform optimal extraction of orders for both fibres.
- Correct the flat-field and the blaze.
- Search for the LFC lines.
- Fit the LFC lines.
- Assign wavelengths to the LFC lines.
- Fit the wavelength solution.
- Complete the wavelength solution with the ThAr one for orders with no LFC flux.
- Save the products with QC KWs.

11.2.10 cal_flux

The recipe measures the absolute efficiency curve. Recipe steps:

- Check the raw frame for saturation.
- Remove the dark current via the scaled MASTER_DARK subtraction
- Measure and subtract inter-order background.
- Perform optimal extraction of orders for both fibres.
- Correct the flat-field.
- Assign wavelength solution to the spectrum.
- Rebin and merge the orders.
- Convert S1D spectrum from detected photoelectrons to physical units (erg/s/cm²/Å).
- Measure and retrieve the flux of the spectrophotometric standard star, and compute absolute efficiency at the reference wavelengths.
- Interpolate efficiency measurements onto the S1D wavelength scale using cubic splines.
- Save the absolute efficiency frame with QC KWs.

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11.2.11 sci_red

The recipe performs the science reduction. Recipe steps:

- Check the raw frame for saturation.
- Remove the dark current via the scaled MASTER_DARK subtraction
- Identify cosmic rays.
- Measure and subtract inter-order background.
- Perform optimal extraction of orders for both fibres.
- Correct the flat-field.
- Assign wavelength solution to the spectrum.
- In simultaneous sky mode:
 - Scale and rebin sky spectrum.
 - Subtract sky.
- In simultaneous reference mode:
 - Measure instrumental drift.
 - Correct instrumental drift.
- Compute barycentric correction using FITS header information.
- Correct wavelength solution from BERV, shifting it to the barycenter of the SS.
- Rebin and merge orders.
- Convert S1D flux into physical units.
- Flux calibrate S1D spectrum (with and without sky subtraction) using absolute efficiency curve.
- Measure fibre centring on integrated guiding image and perform quality control based on specified tolerances.
- Measure flux-weighted mid-exposure time on exposure-meter data and perform quality control.
- Filter residual cosmic hits from S2D spectrum.
- Correct flux distribution in S2D spectrum.
- Compute the radial velocity.
- Compute the CCF bisector.
- Save the S2D, S1D and CCF products with QC KWs.

11.2.12 compu_drift

Recipe computes the drift for a sequence of S2D calibration source spectra. The first S2D in the list is taken as reference. Recipe steps:

- Load S2D images with errors and quality flags
- Extract slices from S2Ds
- Set the first and last orders per detector
- Compute the drift per slice per detector
- Save the QC KWs per detector and per slice
- Save the drift results with QC KWs.

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11.2.13 wave_THAR_THAR

Recipe extracts the S2D spectrum of THAR-THAR frame. Recipe steps:

- Remove the dark current via the scaled MASTER_DARK subtraction
- Perform optimal extraction of orders for both fibres.
- Correct the flat-field and the blaze.
- Save the S2D and S2D_BLAZE products with QC KWs.

11.2.14 wave_LFC_LFC

Recipe extracts the S2D spectrum of LFC-LFC frame. Recipe steps:

- Check the raw frame for saturation.
- Remove the dark current via the scaled MASTER_DARK subtraction
- Perform optimal extraction of orders for both fibres.
- Correct the flat-field and the blaze.
- Save the S2D and S2D_BLAZE products with QC KWs.

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A Installation

A.1 System Requirements

The processing of NIRPS data is very demanding in terms of computing resources. In particular it requires a machine with sufficient memory installed. Less critical but still important is the number of available CPU core sand the amount of available disk space. Because of the memory constraints, the NIRPS pipeline is only supported on 64-bit platforms. The recommended platform is a powerful workstation with a recent 64-bit Linux system. The minimum system configuration is:

- 32 GB of memory
- 4 CPU cores (physical cores)
- 1 TB of free disk space
- GCC 8.3.1 (or newer)

We recommend the user to have more resources:

- 64 GB of memory
- 8 or more CPU cores (physical cores)
- 12 TB of free disk space

The peak memory consumption is with the flat recipe, of 3 GB for each data set, in case of 20 input flats. It could be useful for the user to have a large disk space if a she processes without using interactivity a lot of data. If a user process the data using esorex, for example with a customised system of scripts, it is possible that several esorex based recipes execution in parallel, and consequently memory requirements are higher.

A.2 Installing the Pipeline KIT

The NIRPS pipeline with all the required tools is available from www.eso.org/pipelines, and depending on user's platform we recommend respectively to install via RPM (Linux) or MacPorts (macOS) and if the user's platform is not one of the supported Linux or mac OS, but is a recent Linux or Mac OS X, an installer script is available.

However, the recommended target platform for using the NIRPS DRS is a 64-bit Linux system, since Mac OS X imposes certain restrictions when it comes to running the pipeline. To install the pipeline unpack the kit in a temporary location, go to the top level directory of the unpacked distribution package and execute the installer script as shown in the following example.

Note: The installation script uses the compiler which is found first in the path! If more than one compiler are installed on the system one should make sure that an appropriate 64-bit compiler will be found first when the installation script is executed!

```
tar -zxf espdr-kit-X.Y.Z.tar.gz
cd espdr-kit-X.Y.Z.tar.gz
./install_pipeline
```

Then follow the instructions on the screen. Once the script finishes successfully and the path variables have been set, the installation of the NIRPS pipeline is complete.

Also, the consortium will make the source code available.