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QMOST Pipeline User Manual

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1 Introduction

1.1 Purpose

The QMOST pipeline is a subsystem of the *VLT Data Flow System* (DFS). It is used in two operational environments, for the ESO *Data Flow Operations* (DFO), and for the *Paranal Science Operations* (PSO), in the quick-look assessment of data, in the generation of master calibration data, and data quality control. Additionally, the QMOST pipeline recipes are made public to the user community. The purpose of this document is to describe a typical 4MOST data reduction sequence with the QMOST pipeline.

This manual is a complete description of the data reduction recipes implemented by the the QMOST pipeline, reflecting the status of the QMOST pipeline as of 03.07.2025 (version 0.8.0).

1.2 Acknowledgements

The QMOST pipeline was designed, developed and implemented by Cambridge Astronomical Survey Unit (CASU), Institute of Astronomy, University of Cambridge, UK. The original designers were Jim Lewis and Mike Irwin, who were also responsible for the original implementation of the 4MOST L1 pipeline, upon which this pipeline is based. We also acknowledge the contributions of other current and former members of the group: Francisco Paz-Chinchón, Fabio Herpich, David Homan, and David Murphy.

We thank Armin Gabasch and Lodovico Coccato from ESO for their support throughput the development process.

1.3 Scope

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

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

Additional information the Common Pipeline Library (CPL) and ESOREX can be found respectively at [1], [2]. A description of the instrument is at [?]. The QMOST instrument user manual is at [?].

1.4 Reference and applicable documents

[1] ESO/SDD/DFS, *http://www.eso.org/cpl/*. *CPL home page*. 13

[2] ESO/SDD/DFS, *http://www.eso.org/cpl/esorex.html*. *ESOREX home page*. 13

2 Overview

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

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

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

Science product creation: using pipeline-generated master calibration products, science products are produced for the supported instrument modes (*e.g.*, combined ISAAC jitter stacks; bias-corrected, flat-fielded FORS images, wavelength-calibrated UVES spectra). The accuracy of the science products is limited by the quality of the available master calibration products and by the algorithmic implementation of the pipelines themselves. In particular, adopted automatic reduction strategies may not be suitable or optimal for all scientific goals.

Note however that the QMOST pipeline is not used for scientific data reduction, unlike many other ESO pipelines. The 4MOST consortium provides scientific data reduction as a service for both participating and non-participating surveys using 4MOST with its own Level-1 (L1) pipeline that is not publicly available. This document describes only the ESO QMOST pipeline, or the "QC pipeline" after its main purpose, which is ESO's quality control (QC) process.

ESO instrument pipelines such as the QMOST pipeline consist of a set of data processing modules that can be called from the command line, or automated with tools such as the ESO Data Processing System (EDPS).

The front-end application for launching pipeline recipes is *EsoRex*, included in the pipeline distribution (see Appendix A, page 112). This application can also be downloaded separately from *http://www.eso.org/cpl/esorex.html*

EDPS is a workflow tool used for automating the data reduction process, and is available separately from *http://www.eso.org/sci/software/edps.html*

The 4MOST instrument and the different types of 4MOST raw frames and auxiliary data are described in Sections 3, 6, and 7.

A brief introduction to the usage of the available reduction recipes using EsoRex and EDPS is presented in Section 4. In section 5 we advise the user about known data reduction problems providing also possible solutions.

An overview of the data reduction process, including the input data, and the recipes involved in the calibration cascade is provided in section 8.

More details on the inputs, products, quality control measurements, and controlling parameters of each recipe are given in section 9.

More detailed descriptions of the data reduction algorithms used by the individual pipeline recipes can be found in Section 10.

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

3 4MOST Instrument Description

4MOST is a fibre-fed spectroscopic facility for the VISTA telescope, developed by a consortium led by the Leibniz Institut für Astrophysik Potsdam (AIP), expected to begin operations in 2026.

In this chapter. we give a brief description of 4MOST. More complete documentation can be found in the 4MOST User Manual, downloadable from *http://www.eso.org/sci/facilities/develop/instruments/4MOST.html*

3.1 Instrument overview

4MOST is a fibre fed multi-object spectrograph with a large field of view for the ESO VISTA telescope at Paranal (Figure 3.1). 4MOST deploys 2436 fibres in a 4.1 square degree field of view using a positioner based on tilting spines. The fibres feed one high resolution ($R \approx 20,000$) and two low resolution ($R \approx 6,500$) spectrographs. The spectrographs have fixed configuration 3-channel designs, and each channel has a 6k $\times$ 6k CCD detector.

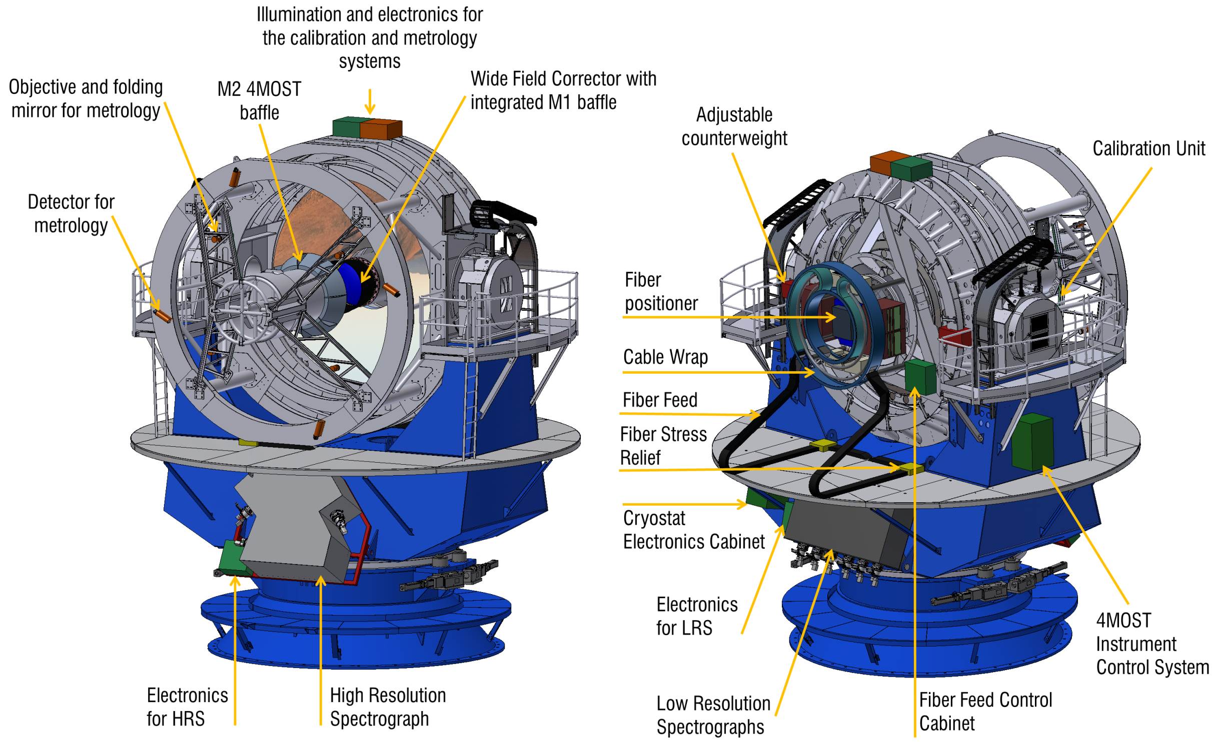

Figure 3.1: *Overview of 4MOST on VISTA.*

The main instrument specifications are summarised in Table 3.2 below.

Parameter	**Design Value**
Field of view (hexagon)	$4.1\ \mathrm{deg}^2$ (diameter $= 2.6°$)
On-sky projected fibre diameter	1.45 arcsec
Smallest target separation	15 arcsec
Fibre multiplex	2436
Low-Resolution Spectrographs (LRS)	
Fibres per spectrograph	812
Spectral resolving power (4000 Å$< \lambda <$ 5000 Å)	$R > \lambda/$Å
Spectral resolving power ($\lambda \geq$ 5000 Å)	$R > 5000$
Wavelength coverage	$3700 - 9500$ Å
High-Resolution Spectrograph (HRS)	
Fibres	812
Spectral resolving power	$R > 18\,500$
Wavelength coverage (blue arm)	$3926 - 4355$ Å
Wavelength coverage (green arm)	$5160 - 5730$ Å
Wavelength coverage (red arm)	$6100 - 6790$ Å

Table 3.2: *4MOST instrument specifications.*

4 Quick start

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

4.1 QMOST pipeline recipes

The current QMOST pipeline is based on 9 recipes involved in the data reduction cascade:

qmost_arc_analyse for wavelength calibration.

qmost_bias_combine to combine bias frames into a master bias.

qmost_dark_combine to combine dark frames into a master dark.

qmost_detector_flat_analyse to combine LED detector flat frames into a master detector flat.

qmost_fibre_flat_analyse for fibre flat fielding to correct pixel to pixel and fibre to fibre response variations.

qmost_fpe_analyse to measure the FPE line wavelengths.

qmost_psf_analyse to measure the fibre PSFs (spatial profile).

qmost_science_process for science data reduction.

qmost_trace to trace the fibres along the dispersion axis.

Two additional recipes are used for measurement of detector properties for monitoring purposes, but are not involved in the normal data reduction cascade:

qmost_detector_noise to measure detector gain and readout noise.

qmost_linearity_analyse to measure detector linearity and detect bad pixels.

4.2 An introduction to ESO instrument pipelines

Before being able to call pipeline recipes on a set of data, the data must be classified, and associated with the appropriate calibrations. The *Data Classification* step consists of tasks such as: "What kind of data am I?", *e.g.*, BIAS, "to which group do I belong?", *e.g.*, to a particular Observation Block or template. *Data Association* is the process of selecting appropriate calibration data for the reduction of a set of raw science frames. Typically, a set of frames can be associated if they share a number of properties, such as instrument and detector configuration. As all the required information is stored in the FITS headers, data association is based on a set of keywords (called "association keywords") and is specific to each type of calibration.

The process of data classification and association is known as data organisation. The *DO Category* is the label assigned to a data type as a result of data classification.

An instrument pipeline consists of a set of data processing modules that can be called from different host applications. This can be done manually from the command line with *EsoRex*.

The process of data organisation and reduction can be automated using workflow tools such as the ESO Data Processing System (EDPS). This system uses a workflow which specifies how the data organisation and reduction steps should be carried out. A suitable EDPS workflow `qmost.qmost_wkf` ships with the QMOST pipeline.

4.2.1 Using EsoRex

EsoRex is a command line utility for running pipeline recipes. It may be embedded by users into data reduction scripts for the automation of processing tasks. The user must classify and associate the data using the information contained in the FITS header keywords (see Section 6, page 27). The user should also take care of defining the input set-of-frames and the appropriate configuration parameters for each recipe run:

The set-of-frames: Each pipeline recipe is run on a set of input FITS data files. When using *EsoRex* the filenames must be listed together with their DO category in an ASCII file, the *set-of-frames* (SOF), that is required when launching a recipe.

Here is an example SOF for the *qmost_trace* recipe:

```
/file_path/QMOST.2025-03-05T19:40:31.779.fits   FIBRE_FLAT_DAY
/file_path/QMOST.2025-03-05T19:41:26.061.fits   FIBRE_FLAT_DAY
/file_path/QMOST.2025-03-05T19:42:20.847.fits   FIBRE_FLAT_DAY
/file_path/QMOST_MASTER_BPM_HRS.fits            MASTER_BPM
/file_path/QMOST_MASTER_BIAS_HRS.fits           MASTER_BIAS
/file_path/QMOST_MASTER_DARK_HRS.fits           MASTER_DARK
/file_path/QMOST_MASTER_DETECTOR_FLAT_HRS.fits  MASTER_DETECTOR_FLAT
/file_path/QMOST_SLIT_MASK_HRS.fits             SLIT_MASK
/file_path/QMOST_REFERENCE_FIBRE_TRACE_HRS.fits REFERENCE_FIBRE_TRACE
```

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

Note that the QMOST pipeline recipes do not verify the correctness of the *DO Category* specified by the user in the SOF. The reason of this lack of control is that the QMOST recipes are just the DRS component of the complete pipeline running on Paranal, where the task of data classification and association is carried out by separate applications. This also allows for more flexibility, where for some applications the user might wish to specify a *DO Category* that does not match the one assigned by the existing classification rules.

EsoRex syntax: The basic syntax to use ESOREX is the following:

esorex [esorex_options] recipe_name [recipe_options] set_of_frames

To get more information on how to customise ESOREX (see also [7]) run the command:

esorex - -help

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

esorex - -create-config

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

esorex - -recipes

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

esorex - -params recipe_name

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

esorex - -help recipe_name

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

esorex - -man-page recipe_name

Recipe configuration: Each pipeline recipe may be assigned an *EsoRex* configuration file, containing the default values of the parameters related to that recipe.

The configuration files are normally generated in the directory `$HOME/.esorex`, and have the same name as the recipe to which they are related, with the filename extension `.rc`. For instance, the recipe *qmost_trace* has its *EsoRex* generated configuration file named `qmost_trace.rc`, and is generated with the command:

esorex - -create-config qmost_trace

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

```
# --keep
# Save optional processed products.
qmost_trace.keep=FALSE
```

In this example, the parameter `qmost_trace.keep` is set to the value `FALSE`. In the configuration file generated by *EsoRex*, one or more comment lines are added containing information about the possible values of the parameter, and an alias that could be used as a command line option.

The recipes provided by the QMOST pipeline are designed to implement a cascade of macro data reduction steps, each controlled by its own parameters. For this reason and to prevent parameter name clashes we specify as parameter prefix not only the instrument name but also the name of the step they refer to. Shorter parameter aliases are made available for use on the command line.

The command

esorex - -create-config recipe_name

generates a default configuration file **recipe_name.rc** in the directory **$HOME/.esorex**[1].

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

esorex - -recipe-config=my_alternative_recipe_config

Recipe parameters are provided in section 9 and their role is described in Section 10.

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

[1]If a number of recipe parameters are specified on the command line, the given values will be used in the created configuration file.

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

esorex qmost_trace qmost_trace.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 *qmost_trace* recipe *keep* parameter to `TRUE`, the following should be typed:

esorex qmost_trace - -keep=TRUE qmost_trace.sof

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

4.2.2 Using EDPS

EDPS automates the classification and association of the data using a workflow and the information contained in the FITS header keywords (see Section 6, page 27).

Please refer to the EDPS tutorial supplied by ESO at *http://www.eso.org/sci/software/edps.html* for full details on EDPS installation and basic use. We assume here that the user has a working EDPS Python virtual environment in /path_edps/ in the following steps.

The EDPS virtual environment should be activated by a command such as:

```
. /path_edps/bin/activate
```

for a Bourne shell (bash, etc.).

The default EDPS configuration is not optimal for the QMOST pipeline since it limits processing to a single thread. We therefore recommend adjusting the configuration file found in:

```
$HOME/.edps/application.properties
```

to increase these defaults. This file is created when EDPS is first run, so this may need to be done first if the file does not yet exist.

A minimal setup for system with low memory or low core count would be:

```
cores={number of cores}
default_omp_threads={number of cores}
```

where the actual number of available cores on the system should be substituted in place of `{number of cores}`, above.

For a larger computer with $\geq$ 32 GB of RAM such as a typical workstation, the pipeline supports parallel processing of the three 4MOST spectrographs, and this can be enabled as follows:

```
processes=3
cores={number of cores}
default_omp_threads={cores / processes}
ordering=bfs
```

where approximately 8GB RAM is needed per parallel processing chain at maximum. The number of processes can be further increased on large systems such as servers to process multiple OBs in parallel for working with large data sets.

After any configuration change, the EDPS server process should be restarted:

```
edps -shutdown
```

Given a set of raw data in `/path_raw/` and static calibration data in `/path_cal/`, the classification step of EDPS can be run with a command such as:

```
edps -w qmost.qmost_wkf -i /path_cal/ /path_raw/ -f
```

where the `-i` flag specifies one or more input directory trees to EDPS, which searches these recursively for FITS files to process. The `-f` flag requests only the classification stage be run.

This command should output a list of files and their corresponding *DO Category*, for example:

```
/path_cal/QMOST_MASTER_BPM_LRS-A.fits MASTER_BPM
/path_cal/QMOST_REFERENCE_FIBRE_TRACE_LRS-A.fits REFERENCE_FIBRE_TRACE
/path_cal/QMOST_SLIT_MASK_LRS-A.fits SLIT_MASK
/path_raw/QMOST.2025-03-05T19:35:54.163.fits FIBRE_FLAT_DAY
/path_raw/QMOST.2025-03-05T19:36:48.541.fits FIBRE_FLAT_DAY
/path_raw/QMOST.2025-03-05T19:37:43.326.fits FIBRE_FLAT_DAY
```

which the user may notice is in the format of a SOF.

To reduce these data, the command should be modified to:

```
edps -w qmost.qmost_wkf -i /path_cal/ /path_raw/ -o /path_out/
```

where the reduced output should appear in `/path_out/` once reduction completes.

After these commands complete, the EDPS server is left running, and can be shut down with:

```
edps -shutdown
```

Note that EDPS keeps state, so repeating the reduction command above does not result in the reduction running again. If this state needs to be cleared, the EDPS server should be shut down as above and the `EDPS_data` directory can be removed to force a reset.

For more information on EDPS, see *http://www.eso.org/sci/software/edps.html*

The QMOST pipeline supports the following meta-targets:

Meta-target (-m)	Description
qc0	All night-time frame types for ESO QC0 process.
qc1calib	All calibration frames and science for ESO QC1 process.
science	Science (default).

and recipe parameter sets:

Parameter set (-rps)	Description
default_parameters	No recipe parameters (recipe defaults).
keep	`keep=TRUE` where supported to keep all outputs.
qc0_parameters	`level=0` where supported for QC0.
science_parameters	Alias for default_parameters.
simulated	For processing 4MOST simulated data.

4.3 Example of data reduction using EsoRex

We suggest using EDPS (see previous section) for reducing normal instrument data taken according to the calibration plan since it provides automation. The process of reducing 4MOST data using EsoRex is manual and has many steps. Nevertheless, for some purposes, the additional flexibility of manual reduction using EsoRex may be needed. A minimal data reduction procedure sufficient to obtain an extracted spectrum is outlined here.

For brevity and simplicity, only the calibration steps necessary for this purpose are included, and the detector calibration chain and night-time calibrations are omitted since they are not technically required. For optimal results, and for real scientific data reduction, these calibrations should of course be included.

We suggest organising the data by OB and detector readout settings (binning and readout speed) to avoid confusion. This can be done based on the hierarchical ESO keywords `OBS ID`, `DET BINX`, `DET BINY`, and `DET READ CURID`. The pipeline was designed with the intent of allowing all three spectrographs to be processed in the same directory, but the user might wish to also separate the spectrographs for some applications, based on `INS PATH`.

In the examples below, we suppose that this has been done, and raw data for LRS-A to be reduced are available in `/path_raw/` with static calibrations in `/path_cal/`. The `esorex` commands for each reduction step are given, and the contents of the SOF are shown.

1. Fibre tracing

```
esorex qmost_trace 001.qmost_trace.sof
```

Contents of `001.qmost_trace.sof`:

```
/path_raw/QMOST.2025-03-05T19:35:54.163.fits     FIBRE_FLAT_DAY
/path_raw/QMOST.2025-03-05T19:36:48.541.fits     FIBRE_FLAT_DAY
/path_raw/QMOST.2025-03-05T19:37:43.326.fits     FIBRE_FLAT_DAY
/path_cal/QMOST_MASTER_BPM_LRS-A.fits            MASTER_BPM
/path_cal/QMOST_SLIT_MASK_LRS-A.fits             SLIT_MASK
/path_cal/QMOST_REFERENCE_FIBRE_TRACE_LRS-A.fits REFERENCE_FIBRE_TRACE
```

2. PSF measurement

```
esorex qmost_psf_analyse 002.qmost_psf_analyse.sof
```

Contents of `002.qmost_psf_analyse.sof`:

```
/path_raw/QMOST.2025-03-05T19:35:54.163.fits     FIBRE_FLAT_DAY
/path_raw/QMOST.2025-03-05T19:36:48.541.fits     FIBRE_FLAT_DAY
/path_raw/QMOST.2025-03-05T19:37:43.326.fits     FIBRE_FLAT_DAY
/path_cal/QMOST_MASTER_BPM_LRS-A.fits            MASTER_BPM
QMOST_FIBRE_TRACE_LRS-A.fits                     FIBRE_TRACE
QMOST_FIBRE_MASK_LRS-A.fits                      FIBRE_MASK
```

3. Simultaneous calibration ThAr arc wavelength solution

```
esorex qmost_arc_analyse 003.qmost_arc_analyse.sof
```

Contents of `003.qmost_arc_analyse.sof`:

```
/path_raw/QMOST.2025-03-05T19:26:54.153.fits     FIBRE_WAVE_SIMUARC
/path_raw/QMOST.2025-03-05T19:29:54.165.fits     FIBRE_WAVE_SIMUARC
/path_raw/QMOST.2025-03-05T19:32:54.171.fits     FIBRE_WAVE_SIMUARC
/path_cal/QMOST_MASTER_BPM_LRS-A.fits            MASTER_BPM
/path_cal/QMOST_ARC_LINELIST_LRS-A.fits          ARC_LINELIST
/path_cal/QMOST_WAVE_MAP_LRS-A.fits              WAVE_MAP
QMOST_FIBRE_TRACE_LRS-A.fits                     FIBRE_TRACE
QMOST_FIBRE_MASK_LRS-A.fits                      FIBRE_MASK
```

4. Measurement of FPE line wavelengths

```
esorex qmost_arc_analyse 004.qmost_fpe_analyse.sof
```

Contents of `004.qmost_fpe_analyse.sof`:

```
/path_raw/QMOST.2025-03-05T19:17:54.168.fits     FIBRE_WAVE_SIMUFPE
/path_raw/QMOST.2025-03-05T19:20:54.181.fits     FIBRE_WAVE_SIMUFPE
/path_raw/QMOST.2025-03-05T19:23:54.164.fits     FIBRE_WAVE_SIMUFPE
/path_cal/QMOST_MASTER_BPM_LRS-A.fits            MASTER_BPM
QMOST_FIBRE_TRACE_LRS-A.fits                     FIBRE_TRACE
QMOST_FIBRE_MASK_LRS-A.fits                      FIBRE_MASK
QMOST_SIMUARC_WAVE_LRS-A.fits                    SIMUARC_WAVE
```

5. Master wavelength calibration of all fibres

```
esorex qmost_arc_analyse 005.qmost_arc_analyse.sof
```

Contents of `005.qmost_arc_analyse.sof`:

```
/path_raw/QMOST.2025-03-05T19:38:37.454.fits     FIBRE_WAVE_DAY
/path_raw/QMOST.2025-03-05T19:39:36.317.fits     FIBRE_WAVE_DAY
/path_raw/QMOST.2025-03-05T19:40:34.354.fits     FIBRE_WAVE_DAY
/path_cal/QMOST_MASTER_BPM_LRS-A.fits            MASTER_BPM
/path_cal/QMOST_WAVE_MAP_LRS-A.fits              WAVE_MAP
QMOST_FIBRE_TRACE_LRS-A.fits                     FIBRE_TRACE
QMOST_FIBRE_MASK_LRS-A.fits                      FIBRE_MASK
QMOST_FPE_LINELIST_LRS-A.fits                    FPE_LINELIST
```

6. Science spectral extraction

```
esorex qmost_science_process 006.qmost_science_process.sof
```

Contents of `006.qmost_science_process.sof`:

```
/path_raw/QMOST.2025-03-05T19:41:48.428.fits     OBJECT
/path_cal/QMOST_MASTER_BPM_LRS-A.fits            MASTER_BPM
/path_cal/QMOST_SENSITIVITY_LRS-A.fits           SENSITIVITY
QMOST_FIBRE_TRACE_LRS-A.fits                     FIBRE_TRACE
QMOST_FIBRE_MASK_LRS-A.fits                      FIBRE_MASK
QMOST_MASTER_WAVE_LRS-A.fits                     MASTER_WAVE
```

5 Known Problems

5.1 FIBINFO tables

The raw FIBINFO tables from the instrument contain some column data types CPL does not support. This results in the following changes in the FIBINFO table columns when they are copied into data products:

- OBJ_SRV is missing. This is a bit vector (TFORM = 'nX') in the raw files, which is not supported by CPL, and is dropped at table read without conversion.
- FIB_ID, OBJ_RLID, SLIT_POS columns are converted from 16-bit (TFORM = 'I') to 32-bit integers (TFORM = '1J').
- OBJ_FLAG, FIB_ST, OBJ_BLID, OBJ_GRID, OBJ_RDID, FIB_USE, FIB_ROOT columns are converted from unsigned byte (TFORM = 'B') to 32-bit integers (TFORM = '1J').

We reiterate that we do not expect these limitations to affect the use of the QC pipeline output files for their intended purposes, and also note that the discussion in this section does not apply to the L1 pipeline, which supports all of these data types and these table columns can therefore pass through unmodified.

5.2 Flagging of saturated pixels

Due to an issue in the 4MOST detector controllers, strongly oversaturated pixels are clipped to the bias level in the raw files. There is no reliable way to identify the pixels that were clipped after the fact by examining the files at the pipeline level since it is too late by the time they reach the pipeline. This means these pixels are not flagged as saturated by the pipeline. Pixels above the ADC saturation level of 65535 counts but below detector saturation seem to usually still be flagged correctly, this effect seems to only occur for strong oversaturation.

This means the saturated pixel count emitted as QC NUM SAT can underestimate the number of saturated pixels, and these pixels also appear in the extracted spectrum. When the core of a strong emission line saturates, this typically results in the line appearing to be split in two in the extracted spectrum. A consequence of this is the bright Ar lines in the red arm ThAr arc spectra can't be used for wavelength calibration, but this effect could also appear in science spectra if there were very bright saturated emission features.

6 Instrument Data Description

4MOST consists of three separate spectrographs that take data simultaneously, all fibre fed from the same fibre positioner. In normal operation when all spectrographs are active, each template executed at the telescope produces three raw data files, one for each spectrograph. For the purposes of pipeline processing, these are treated as independent instruments. There are therefore three parallel chains of execution of the pipeline recipes, one for each spectrograph, and all data files, including calibrations, are separate per spectrograph. The pipelines are set up with the intent that these chains run in parallel using multiple CPU cores, so all intermediate and output file names are tagged with the spectrograph to ensure they are unique. The FITS primary header keyword ESO INS PATH is used to identify the spectrograph and can be CCDHR, CCDLRA or CCDLRB for HRS, LRS-A or LRS-B, respectively.

4MOST data can be separated into *raw* frames and *product* frames. Raw frames are the unprocessed output of the 4MOST instrument observations, while product frames are either the result of the QMOST pipeline processing (as reduced frames, master calibration frames, etc.), or come from external sources (calibration lamp line lists, etc.).

Any raw or product frame can be classified on the basis of a set of keywords read from its header. In the case of raw frames, these are classified by the three hierarchical ESO keyword values: DPR TYPE, DPR CATG, and DPR TECH. In the case of product frames, the classification is given by PRO CATG.

Most kinds of raw frame are typically associated to a single QMOST pipeline recipe. In an automated pipeline environment, this recipe would be launched automatically. For the flat field frame types there are multiple recipes, where each produces a different types of product. For example, a fibre flat frame can be given as input to `qmost_trace`, `qmost_psf_analyse` or `qmost_fibre_flat_analyse` depending on the type of product needed, where these particular recipes are usually executed in the order given.

A product frame may be input to more than one QMOST pipeline recipe, but with the exception of some diagnostic outputs that are not inputs to other recipes, products are created by only one pipeline recipe. In the automatic pipeline environment a product data frame alone would not trigger the launch of any recipe.

In the following all raw and product 4MOST data frames are listed, together with the keywords used for their classification and correct association. The indicated *DO category* is a label assigned to any data type after it has been classified, which is then used to identify the frames listed in the *Set of Frames* (see Section 4.2.1, page 19).

6.1 Raw Data

The raw data files follow the same structure for all three spectrographs. Each spectrograph has three cameras, RED, GREEN and BLUE. In the raw files, a dummy FITS primary header is followed by three IMAGE extensions containing the raw image data for each camera. These are then followed by two FITS binary table extensions, FIBINFO giving information about the target each fibre was positioned on, and METROLOGY reporting metrology measurements made by the instrument metrology cameras on the back-illuminated fibres to position them. The table below summarises this raw file structure.

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
RED_DATA	Unsigned 16-bit integer IMAGE HDU for red channel.

GREEN_DATA	Unsigned 16-bit integer IMAGE HDU for green channel.
BLUE_DATA	Unsigned 16-bit integer IMAGE HDU for blue channel.
FIBINFO	BINTABLE HDU containing the fibre information table.
METROLOGY	BINTABLE HDU containing the metrology table.

The fibre information ("FIBINFO") table appears in both the raw and processed data files. It is defined in full in the Facility Control System - Data Management System Interface Control Document (FCS-DMS ICD). We summarise the definition of the columns in the raw files below.

Description of the FIBINFO extension header keywords (HIERARCH ESO prefix is omitted):

Keyword	**Data Type**	**Description**
OCS RADESYS	string	Used coordinate system; default ICRS.
OCS MAG IDi	string	Magnitude system header dictionary.
OCS SRVi IDi	string	Keywords for mapping of OBJ_SRV bits to surveys.
OCS OFFSET REL ALPHA	float	Relative RA offset (arcsec).
OCS OFFSET REL DELTA	float	Relative DEC offset (arcsec).
OCS OFFSET REL COORD	string	Offset coordinate type

Description of the FIBINFO table columns:

Column	**Data Type**	**Description**
FIB_ID	uint16	Fibre ID.
OBJ_UID	int64	Unique object identifier.
OBJ_NME	char24	Unique name/id of catalogue entry.
OBJ_RA	double	Catalogue object right ascension (deg).
OBJ_DEC	double	Catalogue object declination (deg).
OBJ_PMRA	double	RA proper motion of object (mas/yr).
OBJ_PMDE	double	Dec proper motion of object (mas/yr).
OBJ_ROFF	float	Offset to object right ascension (arcsec).
OBJ_DOFF	float	Offset to object declination (arcsec).
OBJ_PRLX	float	Object parallax (mas).
OBJ_EPOC	float	Epoch of coordinates (yr).
OBJ_SRV	bit[n]	Unique identifier for which surveys and sub surveys a target belongs.
OBJ_FLAG	uint8	DMS processing directives (transient, z-classification, bad weather).
FIB_PHI	double	Ideal PHI, focal surface fibre coordinate (deg).
FIB_THET	double	Ideal THETA, focal surface fibre coordinate (deg).
FIB_ST	uint8	Fibre status: 0: Disabled; non-usable spine 1: Parked; unable to move, but sees light. Used for calibration. 2: Usable; fully functional spine
OBJ_RLID	uint16	Predefined algorithm.
OBJ_BL	float	Object magnitude estimate for blue arm (e.g. SDSS-like AB g-band).
OBJ_BLER	float	Error on OBJ_BL (mag).
OBJ_BLID	uint8	Identifier ID for MAG IDi header dictionary.

OBJ_GR	float	Object magnitude estimate for green arm (e.g. SDSS-like AB r-band).
OBJ_GRER	float	Error on OBJ_GR (mag).
OBJ_GRID	uint8	Identifier ID for MAG IDi header dictionary.
OBJ_RD	float	Object magnitude estimate for red arm (e.g. SDSS-like AB i-band).
OBJ_RDER	float	Error on OBJ_RD (mag).
OBJ_RDID	uint8	Identifier ID for MAG IDi header dictionary.
FIB_USE	uint8	Fibre usage: 0: Simultaneous calibration fibre 1: Object 2: Reference 3: Sky 4: Calibration 5: Active secondary guiding spine 6: Inactive secondary guide spine 7: Telluric standards 8: Spectrophotometric standard
OBJ_WAV	float	Wavelength to target when centroiding (nm).
FIB_ROOT	uint8	Fibre root: 1: HRS 2: LRS-A 3: LRS-B 4: Secondary guiding fibre
SLIT_POS	uint16	Specifies slit position of fibre, numbering from 1.

Description of the METROLOGY table columns:

Column	**Data Type**	**Description**
FIB_ID	uint16	Fibre ID
SUCCESS	uint8	Statement of the fibre target alignment
FIB_ST	uint8	Fibre status from FIBINFO extension
FIB_STOB	uint8	Fibre status at observation
ITERCOAR	uint16	Number of coarse iterations
ITERFINE	uint16	Number of fine iterations
RA_OBS	double	RA before science exposure (deg).
DEC_OBS	double	DEC before science exposure (deg).
PHI_OBS	double	PHI before science exposure (rad).
THETA_OBS	double	THETA before science exposure (rad).
ACC_FOC	double	Estimated accuracy in the focal surface (rad).
ACC_SKY	double	Estimated accuracy on sky (arcsec).
ZANG	double	Zenith angle for fibre (deg).
TILT	double	Fibre tilt angle (deg).

The raw data for each detector are an array of 6272×6288 pixels combined from 4 separate quadrant readouts. Each quadrant is bounded by 32 pixel prescan / overscan strips on all sides.

Each spectrograph is connected to 812 science fibres, arranged on the spectrograph slit as slitlets containing 29 fibres each. The gaps between these slitlets can be seen in Figure 6.1. The slit is oriented parallel to the detector columns (y axis), so y is the spatial axis and x is the spectral axis. The fibres are separated by approximately 6.5 detector pixels in the spatial direction within each slitlet. There are two additional slitlets, one at each end of the slit, each containing 6 simultaneous calibration fibres, fed directly from the 4MOST calibration unit. During scientific observations, these are fed with calibration light from a laser driven light source (LDLS) through a Fabry-Perot Etalon (FPE), attenuated through various neutral density filters used to adjust the brightness of the simultaneous calibration fibres depending on the exposure time being used for the science exposure. This provides a simultaneous wavelength reference on the detector during the science exposures.

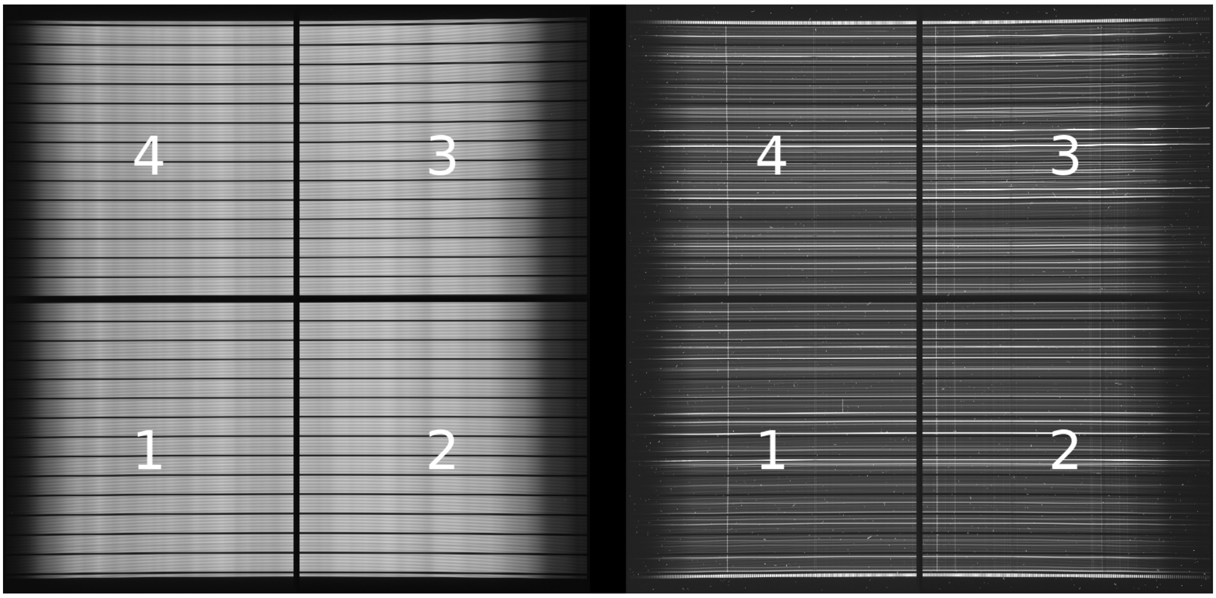

Figure 6.1: *Simulated 4MOST raw fibre flat (left) and science frame (right) showing the 4 amplifiers, with their prescan and overscan regions included. In the raw data, the slit is vertical with different fibres along the y axis (vertical) and wavelength along the x axis..*

The simultaneous calibration fibres are also used as part of the procedure to bootstrap the instrument wavelength calibration, where a ThAr hollow cathode lamp in the calibration unit can be fed into the simultaneous calibration fibres to calibrate the wavelengths of the Fabry-Perot Etalon lines. These exposures are “simuarc” exposures in 4MOST nomenclature and are used in conjunction with “simufpe” exposures of the Fabry-Perot Etalon also through the simultaneous calibration fibres in dedicated recipes to produce a suitable FPE line list. This is then used to do wavelength calibration of the science fibres, which can only be illuminated through the “light sabers” mounted to the telescope secondary supports with LDLS or FPE light.

The wavelength coverage of the spectrographs is fixed, and other than the fibre configuration the only user-adjustable instrument parameters are the detector binning and readout speed. Spatial binning is not permitted due to the extremely close spacing of the fibres, and the only supported spectral binning settings are 1, 2 or 4. Combining these with the two supported readout speeds this leads to a total of 6 possible combinations, although it is unlikely that all of these will be useful. In particular, use of spectral binning causes the spectral PSF to be undersampled, and we therefore anticipate the majority of science spectra will be taken unbinned.

Wavelength calibration exposures must be taken unbinned due to the close spacing of the FPE lines in the blue arm of the low-resolution spectrograph; these lines would overlap in any higher binning setting. Daytime fibre flats are also taken unbinned. Twilight and night-time attached (OB-level) fibre flats are used for correction of fibre throughput and optionally for tracing, and can be taken in any supported binning setting. As a result, there need only be one set of spectroscopic calibration frames and it is not necessary to gather and maintain separate sets for each binning setting. For detector-level calibrations (bias, dark, LED flats), any combination of binning settings that can be reconciled by applying an integer binning factor to the calibration frame before applying it to the target frame are supported, so currently the detector calibrations used are all taken unbinned, which can then be used to reduce any of the binning settings, so again there is only one set of detector calibrations.

We divide raw frames into 4 classes depending on their purpose. Detector calibration frames are used for 2D image reduction to remove detector signature and measure detector properties. Spectroscopic calibration frames are used for spectroscopic data reduction: tracing, wavelength calibration, fibre flat fielding. Facility master spectroscopic calibrations are taken during daytime calibration, however a variety of calibration frames are also taken at night: twilight sky fibre flats, and attached calibration frames in each science OB. Finally, science frames are the raw science observations themselves.

6.1.1 Bias (BIAS)

Type: Detector calibration
DO category: `BIAS`
Processed by: `qmost_bias_combine`

Classification keywords:	Association keywords:	Note:
`DPR CATG = CALIB`	`INS PATH`	Spectrograph
`DPR TYPE = BIAS`	`DET BINX`	Binning along X
`DPR TECH = MOS`	`DET BINY`	Binning along Y
	`DET READ CURID`	Readout speed

6.1.2 Dark (DARK)

Type: Detector calibration
DO category: `DARK`
Processed by: `qmost_dark_combine`

Classification keywords:	Association keywords:	Note:
`DPR CATG = CALIB`	`INS PATH`	Spectrograph
`DPR TYPE = DARK`	`DET BINX`	Binning along X
`DPR TECH = MOS`	`DET BINY`	Binning along Y
	`DET READ CURID`	Readout speed

6.1.3 LED flat (DETECTOR_FLAT)

Type: Detector calibration
DO category: DETECTOR_FLAT
Processed by: qmost_detector_flat_analyse, qmost_detector_noise

Classification keywords:	Association keywords:	Note:
DPR CATG = CALIB	INS PATH	Spectrograph
DPR TYPE = FLAT,LED	DET BINX	Binning along X
DPR TECH = MOS	DET BINY	Binning along Y
	DET READ CURID	Readout speed

6.1.4 Linearity sequence flat (DETECTOR_FLAT_LIN)

Type: Detector calibration
DO category: DETECTOR_FLAT_LIN
Processed by: qmost_linearity_analyse

Classification keywords:	Association keywords:	Note:
DPR CATG = CALIB	INS PATH	Spectrograph
DPR TYPE = FLAT,LIN	DET BINX	Binning along X
DPR TECH = MOS	DET BINY	Binning along Y
	DET READ CURID	Readout speed

6.1.5 Facility daytime fibre flat (FIBRE_FLAT_DAY)

Type: Daytime spectroscopic calibration
DO category: FIBRE_FLAT_DAY
Processed by: qmost_trace, qmost_psf_analyse, qmost_fibre_flat_analyse

Classification keywords:	Association keywords:	Note:
DPR CATG = CALIB	INS PATH	Spectrograph
DPR TYPE = FLAT,DAY	DET BINX	Binning along X
DPR TECH = MOS	DET BINY	Binning along Y
	DET READ CURID	Readout speed

6.1.6 Simultaneous calibration arc (FIBRE_WAVE_SIMUARC)

Type: Daytime spectroscopic calibration
DO category: FIBRE_WAVE_SIMUARC
Processed by: qmost_arc_analyse

Classification keywords:	Association keywords:	Note:
DPR CATG = CALIB	INS PATH	Spectrograph
DPR TYPE = WAVE,DAY,SIMUARC	DET BINX	Binning along X
DPR TECH = MOS	DET BINY	Binning along Y
	DET READ CURID	Readout speed

6.1.7 Simultaneous calibration FPE (FIBRE_WAVE_SIMUFPE)

Type: Daytime spectroscopic calibration
DO category: FIBRE_WAVE_SIMUFPE
Processed by: qmost_fpe_analyse

Classification keywords:	Association keywords:	Note:
DPR CATG = CALIB	INS PATH	Spectrograph
DPR TYPE = WAVE,DAY,SIMUFPE	DET BINX	Binning along X
DPR TECH = MOS	DET BINY	Binning along Y
	DET READ CURID	Readout speed

6.1.8 Facility daytime wavelength calibration (FIBRE_WAVE_DAY)

Type: Daytime spectroscopic calibration
DO category: FIBRE_WAVE_DAY
Processed by: qmost_arc_analyse

Classification keywords:	Association keywords:	Note:
DPR CATG = CALIB	INS PATH	Spectrograph
DPR TYPE = WAVE,DAY	DET BINX	Binning along X
DPR TECH = MOS	DET BINY	Binning along Y
	DET READ CURID	Readout speed

6.1.9 Twilight sky flat (FIBRE_FLAT_SKY)

Type: Night-time spectroscopic calibration
DO category: FIBRE_FLAT_SKY
Processed by: qmost_fibre_flat_analyse

Classification keywords:	Association keywords:	Note:
DPR CATG = CALIB	INS PATH	Spectrograph
DPR TYPE = FLAT,SKY	DET BINX	Binning along X

DPR TECH = MOS	DET BINY	Binning along Y
	DET READ CURID	Readout speed

6.1.10 Attached fibre flat (FIBRE_FLAT_NIGHT)

Type: Night-time spectroscopic calibration
DO category: FIBRE_FLAT_NIGHT
Processed by: qmost_trace, qmost_fibre_flat_analyse

Classification keywords:	Association keywords:	Note:
DPR CATG = CALIB	INS PATH	Spectrograph
DPR TYPE = FLAT,NIGHT	DET BINX	Binning along X
DPR TECH = MOS	DET BINY	Binning along Y
	DET READ CURID	Readout speed

6.1.11 Attached wavelength calibration (FIBRE_WAVE_NIGHT)

Type: Night-time spectroscopic calibration
DO category: FIBRE_WAVE_NIGHT
Processed by: qmost_arc_analyse

Classification keywords:	Association keywords:	Note:
DPR CATG = CALIB	INS PATH	Spectrograph
DPR TYPE = WAVE,NIGHT	DET BINX	Binning along X
DPR TECH = MOS	DET BINY	Binning along Y
	DET READ CURID	Readout speed

6.1.12 Science (OBJECT)

Type: Science
DO category: OBJECT
Processed by: qmost_science_process

Classification keywords:	Association keywords:	Note:
DPR CATG = SCIENCE	INS PATH	Spectrograph
DPR TYPE = OBJECT	DET BINX	Binning along X
DPR TECH = MOS	DET BINY	Binning along Y
	DET READ CURID	Readout speed

6.2 Product Data

Product frames are divided into the same classes as raw frames. The PRO CATG for all product frames is the same as the *DO category*.

As detailed in the previous section, calibrations are on a "per spectrograph" basis and the reader should realise that what is described in this section is repeated for all three spectrographs. The HIERARCH ESO INS PATH keyword in the FITS primary header allows the association of the file to a particular spectrograph. The 2D image calibration products all have variance images stored in separate image extensions to allow for proper error propagation during the calibration of the science data. The variance arrays are also used to flag bad pixels by setting their variance to zero.

Many product frames are processed 2D detector images, except where noted below. The 2D detector calibrations share a common file structure, unless otherwise specified in the individual descriptions below, as follows:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
RED_DATA	32-bit float IMAGE HDU with calibration image for red channel.
RED_DATA_var	32-bit float IMAGE HDU with variance array for red channel.
GREEN_DATA	32-bit float IMAGE HDU with calibration image for green channel.
GREEN_DATA_var	32-bit float IMAGE HDU with variance array for green channel.
BLUE_DATA	32-bit float IMAGE HDU with calibration image for blue channel.
BLUE_DATA_var	32-bit float IMAGE HDU with variance array for blue channel.
FIBINFO	BINTABLE HDU containing the fibre information table.

All detector calibration steps are carried out in the native coordinate system of the detectors, with saved products being produced after prescan / overscan correction and trimming and therefore corresponding to the active pixel dimensions of the detectors of 6144×6160 pixels. The detector calibration frames are in the native orientation of the detectors, matching the raw files.

While we have indicated in the sections below that detector calibration frames are associated based on detector readout settings (binning and readout speed) in addition to spectrograph, in practice mismatched settings can be used if they are compatible, specifically if the binning is related by an integer divisor such that the calibration frame can be binned down in software to match the raw frame being processed. This is done automatically by the pipeline recipes where necessary. An error is raised if incompatible files are given.

The orientations of the spatial and spectral axes on the raw detector images are not consistent, due in part to differing numbers of reflections to reach the detector in each arm, so prior to spectroscopic processing the images are axis flipped to a common orientation, shown in Figure 6.2. In addition to rectifying the differing axis orientations we also swap x and y such that the spectral axis is oriented vertically and the spatial axis is horizontal. This flipped coordinate system applies to all processed 2D detector images emitted by spectroscopic processing, specifically the diagnostic processed image products and masks.

Spectroscopic calibration products are independent of detector readout settings (binning and readout speed) and are therefore associated by spectrograph. OB-level attached calibrations should also be from the same OB. This is not enforced by the pipeline recipes but it is done in the association rules of the EDPS workflow.

A number of pipeline recipes store per-fibre information such as quality control measurements in the FIBINFO tables of the product files, which are detailed as needed in the individual sections discussing these products.

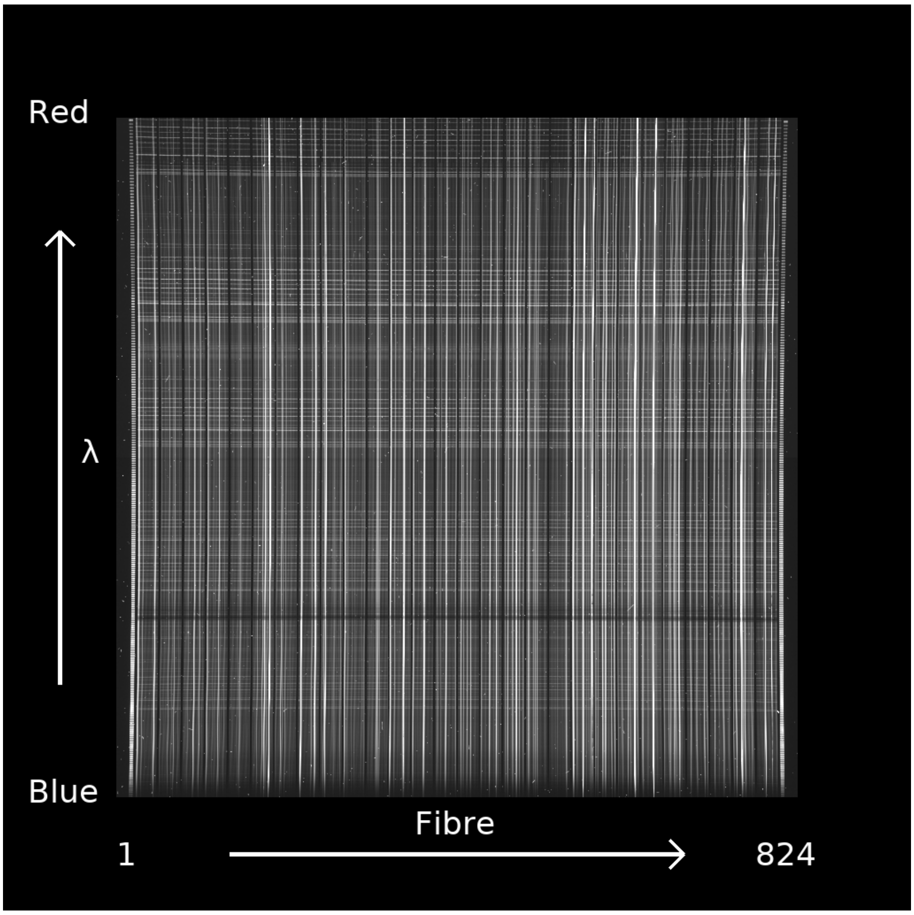

Figure 6.2: *Processed science image, axis flipped to a standard orientation and ready for spectroscopic processing. The spectral axis is now oriented vertically, and wavelength increases with increasing y coordinate (in the FITS convention where the lower-left corner of the image is pixel 1,1). The spatial axis is horizontal and fibre number increases with increasing x coordinate, from left to right..*

The metrology table appears only in the raw files, but its columns are copied into the FIBINFO table of the reduced products, so appear there in the FIBINFO table, after the raw FIBINFO table columns, but before any columns added by the pipeline.

6.2.1 Master bias (MASTER_BIAS)

Type: Detector calibration
DO category: `MASTER_BIAS`
Created by: `qmost_bias_combine`

Association keywords:	Note:
`INS PATH`	Spectrograph

DET BINX	Binning along X
DET BINY	Binning along Y
DET READ CURID	Readout speed

The prescan / overscan regions are used to correct the DC bias, but some 2D residual structure remains, particularly in fast readout mode. A master bias frame generated from a stack of individual bias exposures is used to correct these residuals.

6.2.2 Master dark (MASTER_DARK)

Type: Detector calibration
DO category: MASTER_DARK
Created by: qmost_dark_combine

Association keywords:	Note:
INS PATH	Spectrograph
DET BINX	Binning along X
DET BINY	Binning along Y
DET READ CURID	Readout speed

In 4MOST, dark frames are used primarily for monitoring the dark current to detect problems with the detector vacuum or cooling systems, but can also be used to correct dark current in the data. A master dark frame generated from a stack of individual dark exposures is used for this purpose. The master dark is given in units of ADU/s so it can be easily scaled to the exposure time of the frame to be processed.

6.2.3 Master detector flat (MASTER_DETECTOR_FLAT)

Type: Detector calibration
DO category: MASTER_DETECTOR_FLAT
Created by: qmost_detector_flat_analyse

Association keywords:	Note:
INS PATH	Spectrograph
DET BINX	Binning along X
DET BINY	Binning along Y
DET READ CURID	Readout speed

The 4MOST instrument has LEDs installed near the focal plane, allowing the detector to be illuminated with nearly monochromatic light to be used to obtain 2D flat fields. These are used to correct inter-pixel quantum efficiency variations, but also to correct for differences in the gains of the individual readout amplifiers.

The master detector flat is given in a form suitable to apply both of these corrections simultaneously. The LED flats exhibit structure from the pattern of the illumination, so this is filtered out, the resulting flat is normalised, and each amplifier is multiplied by a correction factor such that dividing by the flat corrects the gains of the individual amplifiers onto a common gain, defined by the first amplifier.

6.2.4 Unfiltered detector flat (UNFILTERED_DETECTOR_FLAT)

Type: Detector calibration
DO category: `UNFILTERED_DETECTOR_FLAT`
Created by: `qmost_detector_flat_analyse`

Association keywords:	Note:
`INS PATH`	Spectrograph
`DET BINX`	Binning along X
`DET BINY`	Binning along Y
`DET READ CURID`	Readout speed

The form of the master detector flat in Section 6.2.3 is not suitable for comparison to track the evolution of the flat field, so the `qmost_detector_flat_analyse` recipe also writes a separate output UNFILTERED_DETECTOR_FLAT for this purpose. This output is the detector flat after stacking and gain correction to remove discontinuities at the amplifier boundaries, but before filtering and without the multiplicative gain correction factors applied. The illumination pattern is thereby retained in the image and it can be used to track evolution of the illumination pattern and intensity.

6.2.5 Readgain table (READGAIN)

Type: Detector calibration
DO category: `READGAIN`
Created by: `qmost_detector_noise`

Association keywords:	Note:
`INS PATH`	Spectrograph
`DET BINX`	Binning along X
`DET BINY`	Binning along Y
`DET READ CURID`	Readout speed

This file reports the measurements of gain and readout noise for each amplifier. The IMAGE extensions here are dummy HDUs, containing no data, and the results of the analysis are reported as QC and DRS header keywords. There is no FIBINFO table.

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
RED_DATA	Dummy IMAGE HDU with results for red detector.
GREEN_DATA	Dummy IMAGE HDU with results for green detector.
BLUE_DATA	Dummy IMAGE HDU with results for blue detector.

6.2.6 Linearity table (LINEARITY)

Type: Detector calibration
DO category: `LINEARITY`
Created by: `qmost_linearity_analyse`

Association keywords:	Note:
`INS PATH`	Spectrograph
`DET BINX`	Binning along X
`DET BINY`	Binning along Y
`DET READ CURID`	Readout speed

This file reports the results of the linearity analysis, and contains a FITS binary table for each detector. Each row of the table contains the linearising polynomial that converts the observed fluxes for a given amplifier into linearised fluxes, as described below.

The linearising polynomial is defined as:

$$p_{\mathrm{lin}} = \sum_{j=1}^{\mathrm{nord}} \mathrm{coefs}[j]\ (p_{\mathrm{obs}})^j \tag{1}$$

where p_{obs} is the observed pixel value in ADU and p_{lin} is the linearised value. The first coefficient ($j = 1$) is always unity.

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
RED_DATA	BINTABLE HDU with linearity solution for red channel.
GREEN_DATA	BINTABLE HDU with linearity solution for green channel.
BLUE_DATA	BINTABLE HDU with linearity solution for blue channel.

Description of the binary table columns:

Column	Data Type	Description

amplifier	int	The number of the amplifier this linearity solution is for.
xmin	int	X pixel lower limit of the detector flat region analysed, numbering from 1.
xmax	int	X pixel upper limit of the detector flat region analysed (inclusive).
ymin	int	Y pixel lower limit of the detector flat region analysed.
ymax	int	Y pixel upper limit of the detector flat region analysed.
nord	int	Degree of polynomial fit.
coefs	double[nord+1]	The polynomial solution coefficients.
rms	double	The RMS of the linearity fit, in ADU.
lin1k	double	The percentage non-linearity at 1000 ADU.
lin5k	double	The percentage non-linearity at 5000 ADU.
lin10k	double	The percentage non-linearity at 10,000 ADU.
lin20k	double	The percentage non-linearity at 20,000 ADU.
lin30k	double	The percentage non-linearity at 30,000 ADU.
lin40k	double	The percentage non-linearity at 40,000 ADU.
lin50k	double	The percentage non-linearity at 50,000 ADU.
nfiles	int	The number of detector flat files analysed.
ngood	int	The number of good files included in the fit after rejection.
adu_med	double[nfiles]	The measured median ADU level for each flat.
exptime	double[nfiles]	The exposure time for each flat (s).
mon_corr	double[nfiles]	The correction factors from the lamp brightness monitoring sequence.
lin_med	double[nfiles]	The linearised counts in ADU for each flat.
fit_flag	int[nfiles]	Boolean, true if the flat was flagged as bad in the fit.

The linearising polynomial is only used as a convenient functional form, and is not the correct underlying model, so as a consequence the coefficients are not themselves physically meaningful. For estimating the prediction error, we therefore take an empirical approach based on assessment of how well the polynomial predicts the counts. This is given in the linearity table as rms and should be used to estimate the prediction error.

6.2.7 Bad pixel mask (BPM)

Type: Detector calibration
DO category: `BPM`
Created by: `qmost_linearity_analyse`

Association keywords:	Note:
`INS PATH`	Spectrograph
`DET BINX`	Binning along X
`DET BINY`	Binning along Y
`DET READ CURID`	Readout speed

This file is produced by the linearity analysis and contains the results of an automated analysis to flag bad pixels based on those pixels found to be outliers in multiple flats from the linearity sequence. The results are given as a bad pixel mask in the form of an unsigned 8-bit integer image, where good pixels are zero (false) and bad pixels have non-zero values (true).

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
RED_DATA	Unsigned byte IMAGE HDU for red channel.
GREEN_DATA	Unsigned byte IMAGE HDU for green channel.
BLUE_DATA	Unsigned byte IMAGE HDU for blue channel.

6.2.8 Trace table (FIBRE_TRACE)

Type: Spectroscopic calibration
DO category: `FIBRE_TRACE`
Created by: `qmost_trace`

Association keywords:	Note:
`INS PATH`	Spectrograph

The trace table defines the spatial (x) position of the centre of gravity of the fibre PSF as a function of the spectral (y) coordinate for each fibre, and is used to define the aperture for spectral extraction.

The trace is given as a polynomial, defined by:

$$x(y) = \sum_{i=0}^{\text{trorder}} \text{trcoefs}[i] \left(\frac{y - y_{\text{ref}}}{y_{\text{ref}}} \right)^i \qquad (2)$$

where y_{ref} is given in the trace table column tryref. The range of validity of the trace polynomial is given by the trace table columns yst and yfn.

Note that all pixel quantities in the trace table are always given in physical (unbinned) detector pixels.

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
trace_RED_DATA	BINTABLE HDU with traces for red channel.
trace_GREEN_DATA	BINTABLE HDU with traces for green channel.
trace_BLUE_DATA	BINTABLE HDU with traces for blue channel.
FIBINFO	BINTABLE HDU containing the fibre information table.

Description of the binary table columns:

Column	Data Type	Description
specnum	int	Index of the extracted spectrum, numbering from 1.
fiblive	int	True if the fibre is live, otherwise false.
yst	int	Start y-position of trace in spectral direction, numbering from 1.
yfn	int	End y-position of trace in the spectral direction, numbering from 1.
tryref	double	Reference y (spectral) pixel for the trace fit.
trrms	double	RMS trace fit residual (pixels).
trorder	int	Order (degree) of the trace polynomial.
trcoefs	double[trorder+1]	Vector column containing trace polynomial coefficients.
npos	int	The number of trace blocks measured.
xpos	double[npos]	Measured trace x (spatial) position for each block.
ypos	double[npos]	Effective y (spectral) position the trace was measured at for each block.
fwhm	float[npos]	Measured spatial FWHM (pix) in block, or -1 if unmeasured.
peak	float[npos]	Peak counts (ADU) in block.
contrast	float[npos]	Peak to trough contrast ([0,1]) for block.

Note: The vector columns all have the same length, equal to the maximum length required by a fibre. Any extra elements are set to NULL (in FITS, this is represented by IEEE Not a Number or NaN for floating point columns).

The polynomial is only used as a convenient functional form for predicting the trace, and is not the correct underlying model, so as a consequence the coefficients are not themselves physically meaningful. For estimating the prediction error, we therefore take an empirical approach based on assessment of how well the polynomial predicts the trace samples. This is given in the trace file as trrms and should be used to estimate the prediction error.

Description of the columns added to the FIBINFO table:

Column	Data Type	Description
TRACE_FWHM_MED_R TRACE_FWHM_MED_G TRACE_FWHM_MED_B	float	Median FWHM of spatial profile (pix).
TRACE_FWHM_RMS_R TRACE_FWHM_RMS_G TRACE_FWHM_RMS_B	float	Robustly estimated RMS FWHM of spatial profile (pix).
TRACE_OFFSET_R TRACE_OFFSET_G TRACE_OFFSET_B	double	Trace offset compared to reference (pix).

6.2.9 Fibre mask (FIBRE_MASK)

Type: Spectroscopic calibration
DO category: `FIBRE_MASK`
Created by: `qmost_trace`

Association keywords:	Note:
INS PATH	Spectrograph

Mask used to define which pixels in the 2D image contain part of a fibre profile, formed from the trace as part of the trace procedure. This is used for scattered light estimation. The mask is given as an unsigned 8-bit integer image where any pixel that is part of a fibre image has a non-zero (true) value and all other pixels have a value of zero (false).

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
mask_RED_DATA	Unsigned byte IMAGE HDU for red channel.
mask_GREEN_DATA	Unsigned byte IMAGE HDU for green channel.
mask_BLUE_DATA	Unsigned byte IMAGE HDU for blue channel.

6.2.10 Master PSF (MASTER_PSF)

Type: Daytime master spectroscopic calibration
DO category: `MASTER_PSF`
Created by: `qmost_psf_analyse`

Association keywords:	Note:
INS PATH	Spectrograph

This file gives a model of the PSF (spatial profile) for each fibre as a function of spectral position, and is used in spectral extraction.

The PSFs for each arm are stored as a 3D data cube, which can be thought of as a set of 2D image planes stacked up along the third (z) axis. The dimensions of this data cube are npsf × nfib × nspec, where npsf is the number of PSF subsamples in the spatial direction, nfib is the number of fibres (=824) and nspec is the number of spectral pixels. Thus each plane of the PSF gives the PSF for an image row on the detector, and there is one plane for each pixel along the spectral axis of the detector. Within the planes, the x direction is the spatial direction and the y direction is the fibre number.

In the spatial direction (x) the PSF is subsampled several times per physical detector pixel (default 5), and a set of FITS-WCS headers specify this by giving the transformation from PSF subsamples $x_{\rm sub}$ (here numbering from 1 per FITS conventions) to physical detector pixels x:

$$x - x_{\rm cen} = {\rm CD1\_1}(x_{\rm sub} - {\rm CRPIX1}) + {\rm CRVAL1} \quad (3)$$

where $x_{\rm cen}$ is the trace centre, defined using the trace polynomial. This can be inverted by:

$$x_{\text{sub}} = (x - x_{\text{cen}} - \text{CRVAL1})/\text{CD1\_1} + \text{CRPIX1} \tag{4}$$

The profile is normalised to a value of WVSCLFAC, so to recover a [0,1] normalisation the profile image should be divided by WVSCLFAC. This is given as an ESO hierarchical DRS header keyword (i.e. HIERARCH ESO DRS WVSCLFAC).

Description of the file structure:

Extension Name	**Description**
Primary	Dummy HDU containing exposure metadata.
prof_RED_DATA	32-bit float IMAGE HDU with PSF cube for red channel.
profvar_RED_DATA	32-bit float IMAGE HDU with PSF error for red channel.
prof_GREEN_DATA	32-bit float IMAGE HDU with PSF cube for green channel.
profvar_GREEN_DATA	32-bit float IMAGE HDU with PSF error for green channel.
prof_BLUE_DATA	32-bit float IMAGE HDU with PSF cube for blue channel.
profvar_BLUE_DATA	32-bit float IMAGE HDU with PSF error for blue channel.
FIBINFO	BINTABLE HDU containing the fibre information table.

Note: the name of the error extensions is misleading. These give the error in the PSF cube in the same format as the PSF cube itself, not variance. This was done for ease of scaling in the implementation. To maintain consistency of the data model with the other files (all of which use variance) the extension was not renamed.

Description of the columns added to the FIBINFO table:

Column	**Data Type**	**Description**
FWHM_R FWHM_G FWHM_B	float	Median FWHM of PSF (pix).

6.2.11 Simultaneous calibration arc wavelength solution (SIMUARC_WAVE)

Type: Daytime master spectroscopic calibration
DO category: `SIMUARC_WAVE`
Created by: `qmost_arc_analyse`

Association keywords:	Note:
`INS PATH`	Spectrograph

This file gives the wavelength solution for the simultaneous calibration fibres derived from the ThAr arc frames, and is the fundamental wavelength calibration upon which all of the FPE solutions are based. The science fibres are flagged as not live since they are not illuminated. See Section 6.2.13 for the description of the file format for wavelength solutions.

6.2.12 FPE line list (FPE_LINELIST)

Type: Daytime master spectroscopic calibration
DO category: `FPE_LINELIST`
Created by: `qmost_fpe_analyse`

Association keywords:	Note:
`INS PATH`	Spectrograph

This file reports the measured wavelength of each FPE mode ("line") for use in wavelength calibration.

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
linelist_RED_DATA	BINTABLE HDU for red channel.
linelist_GREEN_DATA	BINTABLE HDU for green channel.
linelist_BLUE_DATA	BINTABLE HDU for blue channel.

Description of the binary table columns:

Column	Data Type	Description
Wavelength	double	FPE line wavelength (Å) in air.
RMS	double	RMS scatter of individual fibre measurements (Å).
Nfib	int	Number of individual fibre measurements.

6.2.13 Master wavelength solution (MASTER_WAVE)

Type: Daytime master spectroscopic calibration
DO category: `MASTER_WAVE`
Created by: `qmost_arc_analyse`

Association keywords:	Note:
`INS PATH`	Spectrograph

This file gives the wavelength solution for all fibres derived from the daytime facility FPE wavelength calibration frames. This is given as a FITS binary table, containing the wavelength solution itself, and the measurements of the emission features that were used to generate it for evaluation of the goodness of fit. Each row of the binary table gives the information for a single fibre.

The wavelength solution polynomial is defined as:

$$\lambda(x) = \sum_{i=0}^{\mathrm{nord}} \mathrm{coefs}[i]\ (x - x_{\mathrm{ref}})^i \tag{5}$$

where x_{ref} is given in the wavelength solution table as xref, and the resulting wavelength is in units of Ångstroms in air.

All pixel quantities in the wavelength solution table are always given in physical (unbinned) detector pixels and all wavelengths are air wavelength in Angstroms. Note however that the pixel coordinate x here numbers from 1 for the first physical detector pixel in the extracted spectrum, which is not necessarily the first physical pixel of the detector itself if a slit mask was used to exclude some pixels at the start of the spectrum. The physical detector pixel coordinate of the first extracted spectral pixel is given by the FITS header keyword HIERARCH ESO DRS MINYST, which can be used to make this correction as needed; specifically to get the physical detector pixel coordinate x_{phys} corresponding to extracted pixel x:

$$x_{\mathrm{phys}} = x + (\mathrm{MINYST} - 1) \tag{6}$$

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
wave_RED_DATA	BINTABLE HDU with wavelength solution for red channel.
wave_GREEN_DATA	BINTABLE HDU with wavelength solution for green channel.
wave_BLUE_DATA	BINTABLE HDU with wavelength solution for blue channel.
FIBINFO	BINTABLE HDU containing the fibre information table.

Description of the binary table columns:

Column	Data Type	Description
specnum	int	Index of the extracted spectrum, numbering from 1.
fiblive	int	True if the fibre is live, otherwise false.
nord	int	Order (degree) of the wavelength solution polynomial.
coefs	double[nord+1]	Vector column with wavelength solution polynomial coefficients.
xref	double	Reference spectral pixel for the fit.
ngood	int	The number of lines used in the fit after rejection of outliers.
medresid	double	The median of the fit residuals (Å).
fit_rms	double	The RMS fit residual (Å).
wave1	double	The wavelength of the first spectral pixel (Å).
waven	double	The wavelength of the last spectral pixel (Å).
dwave	double	The average spectral dispersion (Å/pix).
nlines	int	The number of detected arc lines in the fibre.
xpos	double[nlines]	Measured spectral pixel coordinate of line.
fwhm	double[nlines]	Measured spectral FWHM (Å) of line, or -1 if unmeasured.
wave_calc	double[nlines]	Calculated wavelength of the line using the wavelength solution (Å).
wave_true	double[nlines]	True wavelength of the line from the line list (Å).

fit_flag	int[nlines]	Boolean flag, false if line was included, true if rejected.
wave_cor	double[nlines]	Wavelength offset compared to master wavelength solution (Å).
peak	float[nlines]	Peak spectral counts (ADU) in line.
contrast	float[nlines]	Peak to continuum contrast ([0,1]) of line.

Note: The vector columns all have the same length, equal to the maximum length required by a fibre. Any extra elements are set to NULL (in FITS, this is represented by IEEE Not a Number or NaN for floating point columns).

The polynomial is only used as a convenient functional form for predicting the wavelengths, and is not the correct underlying model, so as a consequence the coefficients are not themselves physically meaningful. For estimating the prediction error, we therefore take an empirical approach based on assessment of how well the polynomial predicts the wavelengths. This is given in the wavelength solution file as fit_rms and should be used to estimate the prediction error.

6.2.14 Master fibre flat (MASTER_FIBRE_FLAT)

Type: Daytime master spectroscopic calibration
DO category: `MASTER_FIBRE_FLAT`
Created by: `qmost_fibre_flat_analyse`

Association keywords:	Note:
`INS PATH`	Spectrograph

The master fibre flat is used for correcting instrument spectral response variations on scales of tens to hundreds of pixels, in conjunction with the detector flat, and to correct differences in the relative throughputs of the fibres. The fibre flat for each fibre is in the form of a wavelength calibrated, normalised 1D spectrum. The spectra for all fibres are packed into a 2D image, where each image row gives the spectrum for a single fibre. Please refer to 6.2.18 for a full description of the format used for extracted, wavelength calibrated spectra. Fibre normalisation information is emitted to the FIBINFO table.

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
RED_DATA	32-bit float IMAGE HDU with normalised fibre flat for red channel.
RED_DATA_var	32-bit float IMAGE HDU with fibre flat variance for red channel.
GREEN_DATA	32-bit float IMAGE HDU with normalised fibre flat for green channel.
GREEN_DATA_var	32-bit float IMAGE HDU with fibre flat variance for green channel.
BLUE_DATA	32-bit float IMAGE HDU with normalised fibre flat for blue channel.
BLUE_DATA_var	32-bit float IMAGE HDU with fibre flat variance for blue channel.
FIBINFO	BINTABLE HDU containing the fibre information table.

Description of the columns added to the FIBINFO table:

Column	Data Type	Description
MED1_R MED1_G MED1_B	float	The measured median flux in the fibre flat (ADU).
MED2_R MED2_G MED2_B	float	The median flux after correction of the average response (ADU).
MED3_R MED3_G MED3_B	float	The median normalised flux in the fibre (ADU).
NORMLEVEL_R NORMLEVEL_G NORMLEVEL_B	float	Scaling factor used to correct for the relative throughput of the fibre.

6.2.15 Twilight sky fibre flat (SKY_FIBRE_FLAT)

Type: Night-time master spectroscopic calibration
DO category: `SKY_FIBRE_FLAT`
Created by: `qmost_fibre_flat_analyse`

Association keywords:	Note:
`INS PATH`	Spectrograph

The twilight sky fibre flat is used to define the reference ("true") set of relative throughputs of the fibres, and is used to correct for any non-uniform illumination of the fibres in the daytime facility fibre flats. The file format and contents are described in Section 6.2.14.

6.2.16 OB-level wavelength solution (OB_WAVE)

Type: Night-time OB-level spectroscopic calibration
DO category: `OB_WAVE`
Created by: `qmost_arc_analyse`

Association keywords:	Note:
`INS PATH`	Spectrograph
`OBS ID`	Observation Block identifier

The OB-level attached FPE wavelength calibration is used to correct for any wavelength offset resulting from spine tilt or thermal drifts, where the attached wavecal is taken with the spines positioned as they will be for the science exposure.

The file gives an additive correction to the master wavelength solution, so both are used in conjunction to give the final wavelength solution. The file format and contents are described in Section 6.2.13.

6.2.17 OB-level fibre flat (OB_FIBRE_FLAT)

Type: Night-time OB-level spectroscopic calibration
DO category: `OB_FIBRE_FLAT`
Created by: `qmost_fibre_flat_analyse`

Association keywords:	Note:
`INS PATH`	Spectrograph
`OBS ID`	Observation Block identifier

The OB-level attached fibre flat is used to correct for differences in the relative response of the fibres caused by spine tilt, where the attached fibre flat is taken with the spines positioned as they will be for the science exposure. The file format and contents are described in Section 6.2.14.

6.2.18 Science file (SCIENCE)

Type: Science
DO category: `SCIENCE`
Created by: `qmost_science_process`

The output spectral files for each spectrograph contain all of the spectra for an individual observation in one FITS file per spectrograph. The spectra for a given detector/arm all appear in a single 2D 4-byte floating point image extension, with each spectrum occupying a single row in the image. Both sky subtracted and pre-sky subtracted spectra are given. A variance estimate for each spectrum is also given, together with an extension per arm specifying the conversion to flux units (i.e. ADU to $\mathrm{erg/s/cm^2/Å}$). A fibre information, or "FIBINFO" table gives information about the object observed by each fibre, summary QC information for the extracted spectrum in the fibre, and relevant information from the metrology table.

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
RED_DATA	Extracted, wavelength calibrated, sky subtracted spectra for red arm (ADU).
RED_IVAR	Inverse variance array giving uncertainty in above ($\mathrm{ADU^{-2}}$).
RED_DATA_NOSS	Extracted, wavelength calibrated spectra before sky subtraction, red (ADU).
RED_IVAR_NOSS	Inverse variance array giving uncertainty in above ($\mathrm{ADU^{-2}}$).
RED_SENSFUNC	Sensitivity function for red arm ($\mathrm{erg/s/cm^2/Å/ADU}$).

GREEN_DATA	Extracted, wavelength calibrated, sky subtracted spectra for green arm (ADU).
GREEN_IVAR	Inverse variance array giving uncertainty in above (ADU^{-2}).
GREEN_DATA_NOSS	Extracted, wavelength calibrated spectra before sky subtraction, green (ADU).
GREEN_IVAR_NOSS	Inverse variance array giving uncertainty in above (ADU^{-2}).
GREEN_SENSFUNC	Sensitivity function for red arm ($\mathrm{erg/s/cm^2/Å/ADU}$).
BLUE_DATA	Extracted, wavelength calibrated, sky subtracted spectra for blue (ADU).
BLUE_IVAR	Inverse variance array giving uncertainty in above (ADU^{-2}).
BLUE_DATA_NOSS	Extracted, wavelength calibrated spectra before sky subtraction, blue arm (ADU).
BLUE_IVAR_NOSS	Inverse variance array giving uncertainty in above (ADU^{-2}).
BLUE_SENSFUNC	Sensitivity function for blue arm ($\mathrm{erg/s/cm^2/Å/ADU}$).
FIBINFO	BINTABLE HDU containing the fibre information table.

Notes:

- The spectra are given in a consistent internal flux system in ADU.
- The IVAR arrays give inverse variance = $1/\mathrm{variance}$, which is also the weight of the data point in standard least-squares maximum likelihood analysis. These are also used to flag bad pixels, which are set to zero in the IVAR array.
- The sensitivity function extension gives the conversion factor from ADU to physical units. To apply the sensitivity function and obtain flux calibrated spectra in $\mathrm{erg/s/cm^2/Å}$, the image in the *arm*_DATA extension is multiplied by *arm*_SENSFUNC, for example RED_DATA $\times$ RED_SENSFUNC gives a flux calibrated result for the red arm. The inverse variance array should be divided by the square of the sensitivity function to obtain the corresponding inverse variance for the flux calibrated spectrum.
- The NOSS extensions are omitted if sky subtraction is disabled.
- The SENSFUNC extensions are omitted if no sensitivity function (SENSITIVITY input) is provided.

Figure 6.3 shows the 2D image format used for the fibre spectra throughout the pipeline, including the IMAGE extensions of the science file.

The image rows correspond directly to the fibres on the spectrograph slit, i.e. row 1 is the first fibre on the slit, row 2 is the second, etc. and the same correspondence applies to the rows and the quantity SLIT_POS in the FIBINFO table. If a fibre is bad, it is flagged by setting all of the inverse variances to zero (or variances to zero in some other products such as calibrations discussed in the previous and next sections). Bad fibres known to the fibre positioner should also listed as such (FIB_ST == 0) in the FIBINFO table, but it is possible for the pipeline to detect a bad fibre during tracing that was not known to be bad at the time the FIBINFO table was produced in the 4MOST operation system, so the check for all inverse variances in the row being zero is more reliable. Since the first 6 fibres and the last 6 fibres on the slit are simultaneous calibration fibres, these image rows contain the simultaneous calibration spectra.

The wavelength in Å for a given spectral pixel x can be computed using a standard FITS-WCS transformation:

$$\lambda = \mathrm{CD1\_1}(x - \mathrm{CRPIX1}) + \mathrm{CRVAL1} \tag{7}$$

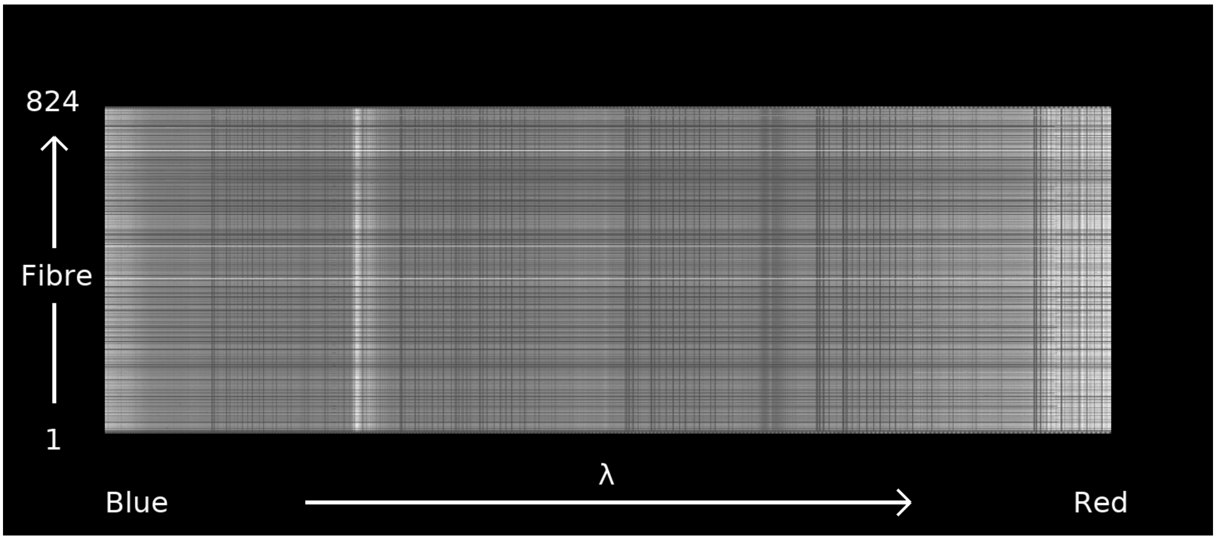

Figure 6.3: *Extracted science spectra from 4MOST simulated data, shown in their native 2D image format (e.g. as one would see examining the science file in ds9). The spectrum for a given fibre is contained in the corresponding row of the image. By referring to the FITS-WCS headers, the wavelengths can be assigned to the pixels. This format provides a compact means to store multi-object spectra, and makes it straightforward to locate and view the neighbouring spectra on the slit to a target of interest for assessment of crosstalk contamination. Since the spectra are on a common wavelength scale, features that are common to all spectra such as telluric features or sky lines appear as vertical lines in the 2D image, and this property can be useful for diagnostic purposes such as to assess if the wavelength calibration or sky subtraction were successful..*

where x numbers from 1 per FITS conventions. The other quantities in the equation are taken directly from the FITS header. The wavelengths are in air as standard for optical spectroscopy. The CTYPE1 = 'AWAV' keyword given in the header should specify this to a compliant FITS-WCS reader (per Greisen et al., 2006, A&A, 446, 747).

To obtain the spectrum for a single object, the fibre number i (numbering from 1 for the first fibre on the slit) for the object needs to be known. If this is not known, the FIBINFO table can be consulted to find the fibre number based on other information about the object such as the 4MOST IAU-format identifier (OBJ_NME) or position on the sky (OBJ_RA, OBJ_DEC). The spectrum is then simply the ith row of the image.

Since the fibres and thus image rows are numbered in the order they appear on the slit, the spectra for the immediately neighbouring objects on the slit can be obtained for assessment of crosstalk contamination / correction by subtracting and adding 1 from the fibre number.

Description of the columns added to the FIBINFO table:

Column	Data Type	Description
NLIN_ARC_R NLIN_ARC_G NLIN_ARC_B	int	Number of good lines used in fibre wavelength solution
RMS_ARC_R	double	RMS of wavelength solution for fibre (Å).

RMS_ARC_G RMS_ARC_B		
FWHM_R FWHM_G FWHM_B	float	Mean FWHM of arc lines in fibre (Å).
HELIO_COR	float	Heliocentric correction applied to fibre (km/s).
WAVE_COR_R WAVE_COR_G WAVE_COR_B	double	Wavelength offset applied to arc solution (Å).
WAVE_CORRMS_R WAVE_CORRMS_G WAVE_CORRMS_B	double	RMS of wavelength offset applied (Å).
EXPTIME	float	Total exposure time for object (s).
SNR_R SNR_G SNR_B	float	Mean signal to noise ratio per pixel.
MEANFLUX_R MEANFLUX_G MEANFLUX_B	float	Mean flux per pixel in extracted spectrum (ADU).

6.3 Optional diagnostic or informational products

6.3.1 Bias difference image (DIFFIMG_BIAS)

DO category: `DIFFIMG_BIAS`
Created by: `qmost_bias_combine`
Emitted when: Reference bias (REFERENCE_BIAS) provided

Difference image for comparison of master bias, formed as MASTER_BIAS − REFERENCE_BIAS.

6.3.2 Dark difference image (DIFFIMG_DARK)

DO category: `DIFFIMG_DARK`
Created by: `qmost_dark_combine`
Emitted when: Reference dark (REFERENCE_DARK) provided

Difference image for comparison of master dark, formed as MASTER_DARK − REFERENCE_DARK.

6.3.3 Detector flat difference image (DIFFIMG_DETECTOR_FLAT)

DO category: `DIFFIMG_DETECTOR_FLAT`
Created by: `qmost_detector_flat_analyse`
Emitted when: Reference detector flat (REFERENCE_DETECTOR_FLAT) provided

Ratio image for comparison of detector flat field, formed as UNFILTERED_DETECTOR_FLAT / REFERENCE_DETECTOR_FLAT.

6.3.4 Processed fibre flat detector image (PROC_FIBRE_FLAT)

DO category: `PROC_FIBRE_FLAT`
Created by: `qmost_fibre_flat_analyse`, `qmost_psf_analyse`, `qmost_trace`
Emitted when: `keep=TRUE`

Processed 2D detector image for fibre flat, before spectral extraction, but after all 2D processing steps including prescan / overscan correction, trimming, 2D bias and dark correction, detector flat fielding, and scattered light correction. Used for trace diagnostic by overplotting the trace solutions, and for diagnosis of 2D processing steps.

6.3.5 Processed wavecal detector image (PROC_FIBRE_WAVE)

DO category: `PROC_FIBRE_WAVE`
Created by: `qmost_arc_analyse`, `qmost_fpe_analyse`
Emitted when: `keep=TRUE`

Processed 2D detector image for wavelength calibration, before spectral extraction, but after all 2D processing steps including prescan / overscan correction, trimming, 2D bias and dark correction, detector flat fielding, and scattered light correction. Used for diagnosis of 2D processing steps.

6.3.6 Processed science detector image (PROC_SCIENCE)

DO category: `PROC_SCIENCE`
Created by: `qmost_science_process`
Emitted when: `keep=TRUE`

Processed 2D detector image for science exposure, before spectral extraction, but after all 2D processing steps including prescan / overscan correction, trimming, 2D bias and dark correction, detector flat fielding, and scattered light correction. Used for diagnosis of 2D processing steps.

6.3.7 Rejection map or cosmic ray mask (COSMIC_RAY_MASK)

DO category: `COSMIC_RAY_MASK`
Created by: `qmost_fibre_flat_analyse`, `qmost_science_process`
Emitted when: `keep=TRUE`, `level=1`

This file is produced as part of PSF spectral extraction, and shows the locations of the pixels rejected as outliers based on goodness of fit of the PSF model. The results are given as a bad pixel mask in the form of a 32-bit integer image, where good pixels are zero (false) and bad pixels have various non-zero values (true), where the value indicates the reason for flagging the pixel (see table below).

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
RED_DATA	32-bit integer IMAGE HDU for red channel.
GREEN_DATA	32-bit integer IMAGE HDU for green channel.
BLUE_DATA	32-bit integer IMAGE HDU for blue channel.

The following table gives the pixel values used in the rejection map:

Symbolic name	Value	Description
GOOD	0	Good pixel
HOT	1	Hot pixel
COLD	2	Cold pixel
CR1	3	Pixel affected by cosmic ray
CR2	4	Discordant pixel next to cosmic ray pixel
SAT	5	Saturated pixel
DISC	6	Pixel flagged as discordant during PSF fitting
OTHER	100	Pixel flagged bad for another reason not in above list

6.3.8 Extracted, uncalibrated master wavelength calibration spectra (MASTER_ARC)

DO category: `MASTER_ARC`
Created by: `qmost_arc_analyse`
Emitted when: `keep=TRUE`

This file records the extracted spectrum of the master wavelength calibration frame immediately following spectral extraction, in native detector pixels, before wavelength calibration. This is the input to the emission feature detection and measurement used for wavelength calibration, and is provided for diagnostic purposes.

The spectra are given in 2D IMAGE extensions in the same layout as the master fibre flat file (Section 6.2.14), but in native detector pixels, so there is no wavelength solution.

The range of physical detector pixels that are extracted and recorded in the IMAGE extension is determined by the slit mask and is not necessarily the entire spectral axis, so the length of the spectral axis of the extracted spectra may be less than the number of detector pixels in the input. The FITS header keywords HIERARCH ESO DRS MINYST and MAXYFN specify the first and last physical detector pixels that were extracted should this information be needed.

6.3.9 Extracted, uncalibrated OB wavelength calibration spectra (OB_ARC)

DO category: `OB_ARC`
Created by: `qmost_arc_analyse`
Emitted when: `keep=TRUE`

This file records the extracted spectrum of the OB-level wavelength calibration frame immediately following spectral extraction, in native detector pixels, before wavelength calibration. See Section 6.3.8 for a full description of these files.

6.3.10 Extracted, uncalibrated simuarc wavelength calibration spectra (SIMUARC_ARC)

DO category: `SIMUARC_ARC`
Created by: `qmost_arc_analyse`
Emitted when: `keep=TRUE`

This file records the extracted spectrum of the simultaneous calibration ThAr wavelength calibration frame immediately following spectral extraction, in native detector pixels, before wavelength calibration. See Section 6.3.8 for a full description of these files.

6.3.11 Extracted, uncalibrated simufpe spectra (FPE_SPECTRUM)

DO category: `FPE_SPECTRUM`
Created by: `qmost_fpe_analyse`
Emitted when: `keep=TRUE`

This file records the extracted spectrum of the simultaneous calibration FPE frame immediately following spectral extraction, in native detector pixels, before wavelength calibration. See Section 6.3.8 for a full description of these files.

6.3.12 Wavelength calibrated master wavelength calibration spectra (MASTER_WARC)

DO category: `MASTER_WARC`
Created by: `qmost_arc_analyse`
Emitted when: `keep=TRUE`

This file records the result of applying the master wavelength solution to the input spectrum used to generate it. It is provided for diagnostic purposes. Since the wavelength calibration is applied by resampling the spectrum to a uniform linear wavelength scale that is the same across all fibres, the FPE lines should appear vertical and unbroken when viewed as a 2D image if the wavelength calibration was successful. The file format is otherwise the same as for the master fibre flat, detailed in Section 6.2.14.

6.3.13 Wavelength calibrated OB wavelength calibration spectra (OB_WARC)

DO category: `OB_WARC`
Created by: `qmost_arc_analyse`
Emitted when: `keep=TRUE`

This file records the result of applying the combined master wavelength solution and OB wavelength solution correction to the input spectrum used to generate the latter. See Section 6.3.12 for a full description of these files.

6.3.14 Wavelength calibrated simuarc wavelength calibration spectra (SIMUARC_WARC)

DO category: `SIMUARC_WARC`
Created by: `qmost_arc_analyse`
Emitted when: `keep=TRUE`

This file records the result of applying the simultaneous calibration ThAr arc wavelength solution to the input spectrum used to generate it. See Section 6.3.12 for a full description of these files.

6.3.15 Extracted, uncalibrated fibre flat spectra (EXTRACTED_FIBRE_FLAT)

DO category: `EXTRACTED_FIBRE_FLAT`
Created by: `qmost_fibre_flat_analyse`
Emitted when: `keep=TRUE`

This file records the wavelength calibrated, extracted spectrum of the fibre flat, before the filtering and normalisation steps used to produce the master fibre flat detailed in Section 6.2.14. It is otherwise in the same format.

6.3.16 Sky subtraction diagnostics file (SKY)

DO category: `SKY`
Created by: `qmost_science_process`
Emitted when: `keep=TRUE`, sky subtraction performed

This file contains diagnostic ancillary information about the sky subtraction. It is likely of interest only to a small subset of expert users of the pipeline, and is not described here. Please refer to the pipeline design document VIS-DER-4MOST-47110-1410-0002 "QC and Level-1 Science Data Reduction Pipeline Description" or the embedded *doxygen* documentation contained within the pipeline source code for details of the file contents, if needed.

6.3.17 Sky subtraction eigenvectors file (EIGEN)

DO category: `EIGEN`
Created by: `qmost_science_process`
Emitted when: `keep=TRUE`, sky subtraction performed

This file reports the results of the PCA decomposition of the sky emission line residuals done after subtraction of the mean sky spectrum. This is used to do a PCA reconstruction to remove residuals in the sky emission lines that were not removed by subtraction of the mean sky spectrum. It is likely of interest only to a small subset of expert users of the pipeline, and is not described here. Please refer to the pipeline design document VIS-DER-4MOST-47110-1410-0002 "QC and Level-1 Science Data Reduction Pipeline Description" or the embedded *doxygen* documentation contained within the pipeline source code for details of the file contents, if needed.

7 Static Calibration Data

The following static calibration data are provided as part of the `qmost-calib` distribution. The indicated *DO category* is a label assigned to any data type after it has been classified, which is then used to identify the frames listed in the *Set of Frames* (see Section 4.2.1, page 19). The PRO CATG for all static calibration frames is the same as the *DO category*. The keywords used for association are also listed, but for all static calibrations these are one file per spectrograph.

7.1 Master bad pixel mask (MASTER_BPM)

DO category: `MASTER_BPM`

Association keywords:	Note:
`INS PATH`	Spectrograph

This file contains the master detector bad pixel mask in the form of an unsigned 8-bit integer image, where good pixels are zero (false) and bad pixels have non-zero values (true).

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
RED_DATA	Unsigned byte IMAGE HDU for red channel.
GREEN_DATA	Unsigned byte IMAGE HDU for green channel.
BLUE_DATA	Unsigned byte IMAGE HDU for blue channel.

7.2 Slit mask (SLIT_MASK)

DO category: `SLIT_MASK`

Association keywords:	Note:
`INS PATH`	Spectrograph

This file defines the detector pixels that are illuminated by the spectrograph optics, and should be included in the trace and resulting extracted spectra. It is a binary mask in the form of an unsigned 8-bit integer image, where good pixels are zero (false) and bad pixels have non-zero values (true). The output trace files and extracted spectra then exclude the ranges of spectral pixels that are set to true in the slit mask. This is used to exclude regions of the detector where the SNR would be too low for reliable tracing, spectral extraction and flat fielding.

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
RED_DATA	Unsigned byte IMAGE HDU for red channel.
GREEN_DATA	Unsigned byte IMAGE HDU for green channel.
BLUE_DATA	Unsigned byte IMAGE HDU for blue channel.

7.3 Master wavelength map (WAVE_MAP)

DO category: `WAVE_MAP`

Association keywords:	Note:
`INS PATH`	Spectrograph

This file gives the approximate central wavelength of each pixel on the detector, and is used to generate the initial guesses of the measured line wavelengths for cross-matching with the reference line list of the calibration lamp or FPE. It consists of a 32-bit float extension for each detector where the value of each pixel is the wavelength in Angstroms. In practice, given that the wavelengths are offset between the fibres and slitlets comprising the 4MOST slit, there are discontinuities in the true wavelengths between the fibres. In the wavelength map since the goal is only an approximate solution these are smoothed to allow for any small offsets in the traces along the slit.

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
RED_DATA	32-bit float IMAGE HDU for red channel.
GREEN_DATA	32-bit float IMAGE HDU for green channel.
BLUE_DATA	32-bit float IMAGE HDU for blue channel.

7.4 ThAr arc line list (ARC_LINELIST)

DO category: `ARC_LINELIST`

Association keywords:	Note:
`INS PATH`	Spectrograph

This file contains the master line list for the ThAr lamp, giving the wavelength of each line for use in wavelength calibration. It was derived from the ESO VLT FLAMES/GIRAFFE line list.

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
linelist_RED_DATA	BINTABLE HDU for red channel.
linelist_GREEN_DATA	BINTABLE HDU for green channel.
linelist_BLUE_DATA	BINTABLE HDU for blue channel.

Description of the binary table columns:

Column	Data Type	Description
Wavelength	double	ThAr line wavelength (Å) in air.

7.5 Sensitivity function (SENSITIVITY)

DO category: `SENSITIVITY`

Association keywords:	Note:
`INS PATH`	Spectrograph

The sensitivity function is used for removing the continuum curvature introduced by the transmission curve of the fibre. It is a static calibration for the QC pipeline, produced using analysis that exists only within the consortium L1 pipeline.

It is given as a 2D image in the same format as the extracted, wavelength calibrated spectra (see Section 6.2.18), in units of $\mathrm{ergs/cm^2/e-}$.

Description of the file structure:

Extension Name	Description
Primary	Dummy HDU containing exposure metadata.
sens_RED_DATA	32-bit float IMAGE HDU for red channel.
sens_GREEN_DATA	32-bit float IMAGE HDU for green channel.
sens_BLUE_DATA	32-bit float IMAGE HDU for blue channel.

7.6 Reference frames

A number of recipes take a reference frame as an optional input in the SOF. These references are used to do quality control by comparing the newly generated master frame to the reference pixel by pixel. Supplying these references produces additional QC parameters, and in the case of detector calibrations, also produces extra difference image outputs (see Sections 6.3.1, 6.3.2, 6.3.3).

The reference images are otherwise identical to the corresponding master calibration to which they are compared, as shown in the following table:

Normal PRO CATG	Reference PRO CATG
MASTER_BIAS	REFERENCE_BIAS
MASTER_DARK	REFERENCE_DARK
UNFILTERED_DETECTOR_FLAT	REFERENCE_DETECTOR_FLAT
FIBRE_TRACE	REFERENCE_FIBRE_TRACE
MASTER_WAVE	REFERENCE_WAVE

so we do not repeat the descriptions of the file format and contents here.

The pipeline includes the capability of generating the reference bias, dark, detector flat and wavelength solution files by passing the recipe parameter `reference=TRUE` to the appropriate recipe. This only changes the FITS headers of the emitted product, which is otherwise identical to the normal product.

7.6.1 Reference bias (REFERENCE_BIAS)

DO category: `REFERENCE_BIAS`
Created by: `qmost_bias_combine`

Association keywords:	Note:
`INS PATH`	Spectrograph
`DET BINX`	Binning along X
`DET BINY`	Binning along Y
`DET READ CURID`	Readout speed

7.6.2 Reference dark (REFERENCE_DARK)

DO category: `REFERENCE_DARK`
Created by: `qmost_dark_combine`

Association keywords:	Note:
`INS PATH`	Spectrograph
`DET BINX`	Binning along X
`DET BINY`	Binning along Y
`DET READ CURID`	Readout speed

7.6.3 Reference detector flat (REFERENCE_DETECTOR_FLAT)

DO category: `REFERENCE_DETECTOR_FLAT`
Created by: `qmost_detector_flat_analyse`

Association keywords:	Note:
INS PATH	Spectrograph
DET BINX	Binning along X
DET BINY	Binning along Y
DET READ CURID	Readout speed

7.6.4 Reference trace table (REFERENCE_FIBRE_TRACE)

DO category: REFERENCE_FIBRE_TRACE

Association keywords:	Note:
INS PATH	Spectrograph

This file provides a reference set of fibre traces, and plays a role in the trace analysis, where it is used to detect bad fibres, in addition to providing a reference trace set for comparison QC. It must have all fibres populated, so is generated specially based on observations taken during commissioning and supplied as a static calibration. If it is not given, there is no automated bad fibre detection, so the FIB_ST fibre status flags in the FIBINFO table (populated by the 4MOST operation system) must be correct.

In practice, due to a number of fibres with low and variable throughput in the 4MOST positioner, this input is *required* to process all data taken with the fibre positioner, so can only be omitted for specialised laboratory test data sets where all fibres are well illuminated.

7.6.5 Reference wavelength solution (REFERENCE_WAVE)

DO category: REFERENCE_WAVE
Created by: qmost_arc_analyse

Association keywords:	Note:
INS PATH	Spectrograph

This file is used to supply an initial wavelength solution for each fibre during wavelength calibration (one that is somewhat less crude than the master wavelength map). This improves reliability of the wavelength solutions, particularly in the case of FPE due to the zero point ambiguity resulting from periodicity of the FPE line wavelengths. It will also be generated during commissioning with the full fibre complement. It is not required to run the pipeline, and tests based on lab data indicate the solutions using only the master wavelength map are quite reliable, but the use of the reference is recommended. It is also used to do comparison QC.

8 Data Reduction

8.1 Data reduction overview

The main steps required to reduce 4MOST data are detailed in this section. We also indicate the corresponding PRO CATG for each calibration frame in the discussion below.

- Correct for detector signature: bias, dark current, detector flat field. The detector prescan / overscan regions are used to measure the bias level, and the appropriate master calibrations (MASTER_BIAS, MASTER_DARK, and MASTER_DETECTOR_FLAT) are used to apply the corresponding 2D corrections.
- Detect and trace the individual fibre images on the detector to produce a trace table, giving the spatial pixel at which the centre of each spectral pixel is found. This is done by the recipe `qmost_trace`, and the results are stored to calibration files FIBRE_TRACE and FIBRE_MASK for use by subsequent steps.
- Subtract scattered light background from the 2D image. The FIBRE_MASK produced by the trace step is used to define the regions of the detector not occupied by fibre images to be used for measurement of the scattered light background.
- Spectral extraction, where the 2D detector image is converted into a 1D spectrum for each fibre. The FIBRE_TRACE is used to define the location of the fibres, and a PSF file (MASTER_PSF) typically made from the same raw files as the traces is also used for PSF-weighted extraction.
- Wavelength calibration, to define the mapping from spectral pixel to wavelength. This step is quite complicated for 4MOST since it is not possible to measure a spectrum of the ThAr lamp used as the absolute wavelength standard through the science fibres. This must instead be bootstrapped by wavelength calibrating the simultaneous calibration fibres (SIMUARC_WAVE), and then using the calibrated simultaneous calibration fibres to measure the wavelengths of the Fabry-Perot Etalon (FPE) lines, resulting in a line list (FPE_LINELIST). The FPE wavelengths are then used to calibrate the science fibres resulting in the final master wavelength solution (MASTER_WAVE).
- OB-level wavelength solution correction. Due to the tilting spine design of 4MOST, the fibre tilt can affect the wavelengths, so an OB-level correction to the facility daytime master wavelength solution (OB_WAVE) is derived by taking OB-level attached FPE wavelength calibrations at the tilt to be used for the science observation.
- Resampling. The wavelength calibration and heliocentric correction are applied to the spectrum by resampling the spectrum onto a uniform linear wavelength scale. This slightly oversamples the input spectrum to preserve resolution, and conserves flux.
- Fibre flat fielding. This is primarily to correct for response variations between fibres, but variations over small wavelength intervals (predominantly pixel to pixel up to a few tens of pixels) are also corrected. The daytime facility calibration results in a master fibre flat field (MASTER_FIBRE_FLAT). However, as for wavelength calibration, fibre tilt affects the relative fibre responses and is corrected using an OB-level attached fibre flat calibration (OB_FIBRE_FLAT). The reference set of fibre responses is defined by twilight sky flat fields (SKY_FIBRE_FLAT). The science spectral extraction combines all of these corrections to define the final normalisation of each fibre.

- Sky subtraction. The spectrum of the night sky emission is defined using the sky fibres observed in each field, and subtracted from the spectra. Sky emission line residuals are corrected with the aid of the spectrum in weakly illuminated science fibres.
- Sensitivity function correction. Spectra are emitted in native units (ADU) and are still modulated by the overall instrument response on scales larger than a few tens of pixels. Should a spectrum with a flat response be required in physical units, the sensitivity function is given in a SENSFUNC extension of the science spectral file. These are derived from observations of standard stars. The final stage of `qmost_science_process` is to insert this extension into the output file. In the ESO QC pipeline, it is taken from a static calibration file (SENSITIVITY) and this pipeline does not have the capability of rederiving the sensitivity function.

8.2 Required input data

- Static calibration files:
  - Master bad pixel mask (MASTER_BPM).
  - Slit mask (SLIT_MASK).
  - Master wavelength map (WAVE_MAP).
  - ThAr arc line list (ARC_LINELIST).
  - Static sensitivity function (SENSFUNC, optional).
  - Reference fibre trace (REFERENCE_FIBRE_TRACE). This input is optional in the implementation, but it is effectively required for data taken with the fibre positioner, otherwise the fibres may not be numbered correctly.
- Raw frames:
  - Bias (BIAS, optional).
  - Dark (DARK, optional).
  - LED detector flat (DETECTOR_FLAT, optional).
  - Facility daytime fibre flat (FIBRE_FLAT_DAY).
  - Simultaneous calibration arc (FIBRE_WAVE_SIMUARC).
  - Simultaneous calibration FPE (FIBRE_WAVE_SIMUFPE).
  - Facility daytime FPE wavelength calibration (FIBRE_WAVE_DAY).
  - Twilight sky fibre flat (FIBRE_FLAT_SKY, optional).
  - OB-level attached fibre flat (FIBRE_FLAT_NIGHT, optional).
  - OB-level attached FPE wavelength calibration (FIBRE_WAVE_NIGHT, optional).
  - Raw science frames (OBJECT).
- Calibration data products:
  - Master bias (MASTER_BIAS, optional).
  - Master dark (MASTER_DARK, optional).

- Master detector flat (MASTER_DETECTOR_FLAT, optional).
- Trace table (FIBRE_TRACE).
- Fibre mask (FIBRE_MASK).
- Master PSF (MASTER_PSF).
- Simultaneous calibration arc wavelength solution (SIMUARC_WAVE).
- FPE line list (FPE_LINELIST).
- Master wavelength solution (MASTER_WAVE).
- Master fibre flat (MASTER_FIBRE_FLAT, optional).
- Twilight sky fibre flat (SKY_FIBRE_FLAT, optional).
- OB-level fibre flat (OB_FIBRE_FLAT, optional).
- OB-level wavelength solution correction (OB_WAVE).

Calibration data products can be generated from raw data using the pipeline recipes. Alternatively the user may use calibration products obtained from the ESO archive or from the ESO Data Flow Operation department.

Since the process of production of the FPE_LINELIST is particularly complicated, several steps of the chain and their corresponding raw input files can potentially be skipped by obtaining this calibration product, for example in cases where it does not need to be remeasured for analysis with modest requirements on the accuracy of wavelength calibration. In this case, the SIMUARC_WAVE is also not needed since it is only used to produce the FPE_LINELIST.

Steps marked as optional are used in full scientific grade data reduction, but are not strictly needed, and for non-critical purposes the pipeline can be run without them. In practice, the 4MOST detectors have low dark current, so dark frames and the master dark are always optional even in scientific grade data reduction. We do not recommend omitting the master bias and detector flat frames however since there is some structure in the 2D bias, and the detector flat field is used for gain correction of the amplifiers.

8.3 Reduction cascade

4MOST data reduction follows the following sequence. A short description of the available recipes is given in section 4.1. In parenthesis we provide the value of the DO category corresponding to each frame.

To produce the master calibrations:

- Run **qmost_bias_combine** on a set of bias frames (BIAS) to make a master bias (MASTER_BIAS).
- Run **qmost_bias_combine** on a set of dark frames (DARK) to make a master dark (MASTER_DARK).
- Run **qmost_detector_flat_analyse** on a set of LED detector flat frames (DETECTOR_FLAT) to make a master detector flat (MASTER_DETECTOR_FLAT).
- Run **qmost_trace** on a set of daytime facility fibre flat frames (FIBRE_FLAT_DAY) to trace the fibre images (FIBRE_TRACE) and emit a fibre mask (FIBRE_MASK).

- Run **qmost_psf_analyse** on typically the same set of daytime facility fibre flat frames (FIBRE_FLAT_DAY) to measure the PSF (spatial profile) and produce a master PSF file (MASTER_PSF).
- Run **qmost_arc_analyse** on a set of simultaneous calibration ThAr arc ("simuarc") frames (FIBRE_WAVE_SIMUARC) to make a wavelength solution for the simultaneous calibration fibres (SIMUARC_WAVE).
- Run **qmost_fpe_analyse** on a set of simultaneous calibration FPE ("simufpe") frames (FIBRE_WAVE_SIMUFPE) to make an FPE line list (FPE_LINELIST).
- Run **qmost_arc_analyse** on a set of daytime facility fibre FPE wavecal frames (FIBRE_WAVE_DAY) to make a wavelength solution for all fibres.
- Run **qmost_fibre_flat_analyse** on a set of daytime facility fibre flat frames (FIBRE_FLAT_DAY), typically the same set as for tracing, above, to make a master fibre flat (MASTER_FIBRE_FLAT). This step is after wavelength calibration since it needs the wavelength solution to divide out the lamp spectrum properly.
- Run **qmost_fibre_flat_analyse** on a set of twilight sky fibre flat frames (FIBRE_FLAT_SKY) to measure the master set of relative fibre throughputs (SKY_FIBRE_FLAT).

The following steps are carried out per OB:

- Run **qmost_trace** on the OB-level attached fibre flat (FIBRE_FLAT_NIGHT) to trace the fibre images (FIBRE_TRACE) and emit a fibre mask (FIBRE_MASK).
- Run **qmost_fibre_flat_analyse** on the OB-level attached fibre flat (FIBRE_FLAT_NIGHT) to measure the OB-level correction to the relative fibre throughputs (OB_FIBRE_FLAT).
- Run **qmost_arc_analyse** on the OB-level attached FPE wavecal (FIBRE_WAVE_NIGHT) to measure the OB-level correction to the wavelength solution (OB_FIBRE_WAVE).
- Run **qmost_science_process** to process the science frame (OBJECT). The extracted, calibrated spectra are emitted to the science file (SCIENCE).

Figure 8.1 is a flow chart showing the inputs required to run `qmost_science_process` and how they are generated, intended for beginners or those who are less familiar with ESO pipelines.

The standard means of representing this for ESO pipelines is an association map, which is shown in 8.2 and shows the main data products involved in the data reduction cascade in a standardised form. It summarises the dependencies between raw data, calibration products and recipes involved in the correction of the instrument signature and reduction of science data.

Examples of set of frames for each recipe are provided in section 9.

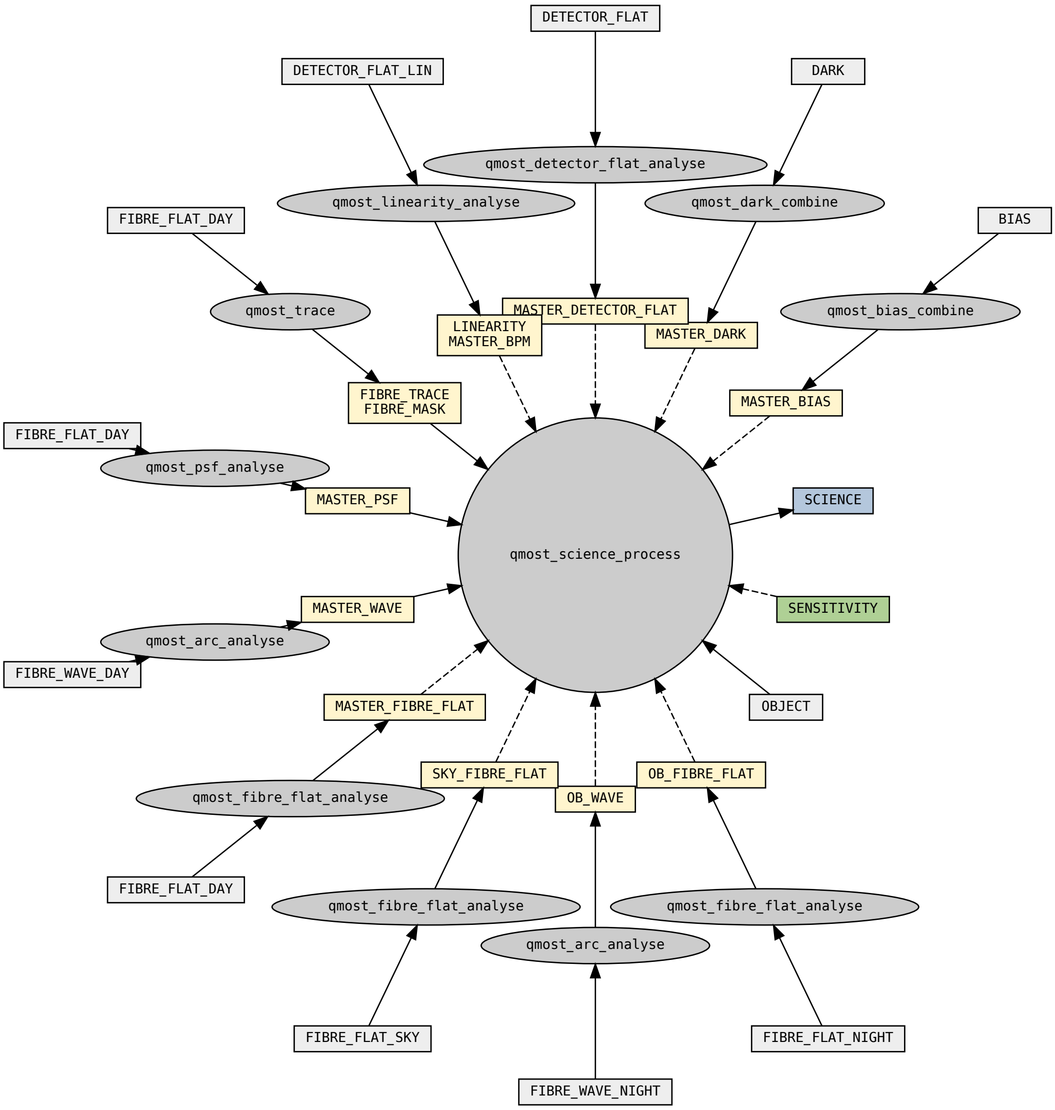

Figure 8.1: *Overview diagram showing the relationship between raw data (light grey rectangles), calibration recipes (dark grey ellipses), calibration frames (yellow boxes) and the way these provide inputs to the main recipe for processing science data qmost_science_process (central dark grey circle). Mandatory paths are indicated with solid lines and optional paths with dashed lines. The main science data path is seen at the right of the diagram where an input OBJECT raw frame is processed to the final SCIENCE output containing the extracted spectra (blue rectangle). Static calibration data are shown as green rectangles. In the case of qmost_science_process the only direct static calibration taken as input is the sensitivity function..*

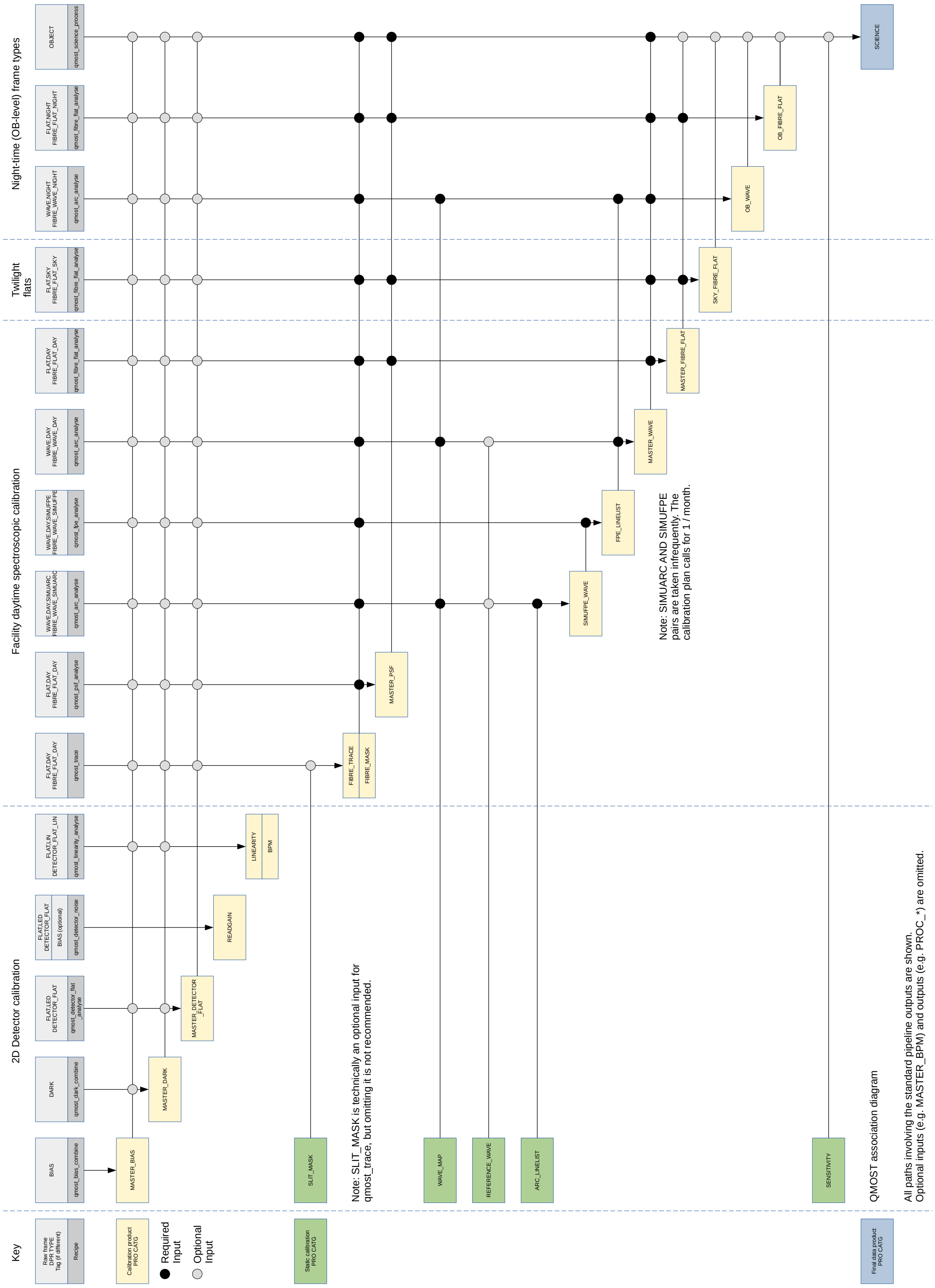

Figure 8.2: *QMOST Association Map.*

9 Pipeline Recipe Interfaces

In this section we detail the input and output of each recipe. The first entry in each table of inputs between the horizontal ruled lines is the raw input, where if multiple raw frames are given, they are stacked. The remaining inputs are calibration data taken from the output of other recipes, the calibration database, or static calibration files provided in `qmost-calib`.

We also provide a list of the pipeline products for each recipe, indicating the value of the FITS keyword HIERARCH ESO PRO CATG (in short PRO.CATG), under what conditions (e.g. recipe parameters) the file is emitted, and a short description. The output file names are generated programmatically based on PRO.CATG and spectrograph. For the product with PRO.CATG "tag" for spectrograph "spec" the output file name is `QMOST_`*tag_spec*`.fits` where "spec" is one of "HRS", "LRS-A" or "LRS-B". For example, the science spectrum for HRS would be emitted to `QMOST_SCIENCE_HRS.fits` and the master fibre flat for LRS-B to `QMOST_MASTER_FIBRE_FLAT_LRS-B.fits` in the current directory. These are the default file names the recipes themselves write, but note that esorex can optionally be instructed to rename the recipe product files following recipe execution, depending on its command line options such as `--output-prefix`.

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

Association keyword	Information
HIERARCH ESO DPR TYPE	Data type
HIERARCH ESO INS PATH	Spectrograph
HIERARCH ESO DET BINX	Detector bin X
HIERARCH ESO DET BINY	Detector bin Y
HIERARCH ESO DET READ CURID	Detector readout speed
HIERARCH ESO PRO CATG	Product category

Quality control parameters are listed in a table for each recipe. These are stored in relevant pipeline products. The full definitions of the quality control parameters are given in the form of a VLT data dictionary `ESO-DFS-DIC.QMOST_QC` which is available in the `qmostc` sub-package of the QMOST pipeline distribution kit, in the subdirectory `dic/`.

More information on instrument quality control can be found on *http://www.eso.org/qc*

The recipe parameters are given in a table following the quality control parameters. The defaults were chosen to be suitable for automated 4MOST data reduction and usually do not need to be adjusted.

9.1 qmost_arc_analyse

Stack individual wavelength calibration arc frames, and do a boxcar extraction. Identify emission features in the extracted spectrum and match to a line list. Solve for polynomial wavelength solution.

This recipe has 3 modes depending on the type of input given. We give a separate input and output table for each below.

9.1.1 Input and output for daytime FPE wavelength calibration

Input DO.CATG	Optional?	Short description
FIBRE_WAVE_DAY	Required	Raw daytime FPE wavecal frames
MASTER_BIAS	Optional	Master bias
MASTER_DARK	Optional	Master dark
MASTER_DETECTOR_FLAT	Optional	Master detector flat
MASTER_BPM	Optional	Master bad pixel mask
LINEARITY	Optional	Master linearity table
FIBRE_TRACE	Required	Master fibre trace
FIBRE_MASK	Required	Master fibre mask
FPE_LINELIST	Required	FPE line list
WAVE_MAP	Required	Master wavelength map
REFERENCE_WAVE	Optional	Reference wavelength solution

Output PRO.CATG	Condition	Short description
MASTER_WAVE	`reference=FALSE`	Master wavelength solution
REFERENCE_WAVE	`reference=TRUE`	Reference wavelength solution
PROC_FIBRE_WAVE	`keep=TRUE`	Processed, stacked 2D image
MASTER_ARC	`keep=TRUE`	Extracted arc spectrum
MASTER_WARC	`keep=TRUE`	Wavelength calibrated arc spectrum

9.1.2 Input and output for night-time OB-level FPE wavelength correction

Input DO.CATG	Optional?	Short description
FIBRE_WAVE_NIGHT	Required	Raw OB-level FPE wavecal frame
MASTER_BIAS	Optional	Master bias
MASTER_DARK	Optional	Master dark
MASTER_DETECTOR_FLAT	Optional	Master detector flat
MASTER_BPM	Optional	Master bad pixel mask
LINEARITY	Optional	Master linearity table
FIBRE_TRACE	Required	Fibre trace
FIBRE_MASK	Required	Fibre mask
FPE_LINELIST	Required	FPE line list
MASTER_WAVE	Required	Master wavelength solution

Output PRO.CATG	Condition	Short description
OB_WAVE	Always	OB wavelength solution correction
PROC_FIBRE_WAVE	`keep=TRUE`	Processed, stacked 2D image
OB_ARC	`keep=TRUE`	Extracted arc spectrum
OB_WARC	`keep=TRUE`	Wavelength calibrated arc spectrum

9.1.3 Input and output for simultaneous calibration arc wavelength solution

Input DO.CATG	Optional?	Short description
FIBRE_WAVE_SIMUARC	Required	Raw simuarc frames
MASTER_BIAS	Optional	Master bias
MASTER_DARK	Optional	Master dark
MASTER_DETECTOR_FLAT	Optional	Master detector flat
MASTER_BPM	Optional	Master bad pixel mask
LINEARITY	Optional	Master linearity table
FIBRE_TRACE	Required	Master fibre trace
FIBRE_MASK	Required	Master fibre mask
ARC_LINELIST	Required	ThAr arc line list
WAVE_MAP	Required	Master wavelength map
REFERENCE_WAVE	Optional	Reference wavelength solution

Output PRO.CATG	Condition	Short description
SIMUARC_WAVE	Always	Simultaneous calibration fibre wavelength solution
PROC_FIBRE_WAVE	`keep=TRUE`	Processed, stacked 2D image
SIMUARC_ARC	`keep=TRUE`	Extracted arc spectrum
SIMUARC_WARC	`keep=TRUE`	Wavelength calibrated arc spectrum

9.1.4 Quality control

QC keyword	Description
NUM SAT	Number of saturated pixels
OS MED AMPn	Median bias level in prescan region (ADU)
OS RMS AMPn	RMS of bias level in prescan region (ADU)
IMCOMBINE MEAN	Mean background level in images that were stacked (ADU)
IMCOMBINE RMS	RMS of background levels in images that were stacked (ADU)
IMCOMBINE MIN	Minimum background level in images that were stacked (ADU)
IMCOMBINE MAX	Maximum background level in images that were stacked (ADU)
IMCOMBINE NOISE MEAN	Mean noise level in images that were stacked (ADU)
IMCOMBINE NUM COMBINED	Number of frames combined
IMCOMBINE NUM INPUTS	Number of input frames
IMCOMBINE NUM REJECTED	Total number of rejected pixels in stacking
EXT FLUX MED	Median of extracted counts over fibres (ADU)
EXT FLUX RMS	RMS of extracted counts over fibres (ADU)
EXT FLUX MIN	Minimum extracted counts over fibres (ADU)
EXT FLUX MINSPC	Fibre with minimum extracted counts
EXT FLUX MAX	Maximum extracted counts over fibres (ADU)
EXT FLUX MAXSPC	Fibre with maximum extracted counts
EXT SN MED	Median SNR over fibres
EXT SN RMS	RMS of SNR over fibres
EXT SN MIN	Minimum SNR over fibres

EXT SN MINSPC	Fibre with minimum SNR
EXT SN MAX	Maximum SNR over fibres
EXT SN MAXSPC	Fibre with maximum SNR
SCATTL MED	Median scattered light (ADU)
SCATTL RMS	RMS of scattered light (ADU)
SCATTL RESID MED	Median scattered light residual (ADU)
SCATTL RESID RMS	RMS of scattered light residual (ADU)
WAVE LINES TOT	Total arc lines in all wavelength solutions
WAVE FWHM MED	Median FWHM of all good arc lines (Å)
WAVE FWHM RMS	Sigma FWHM of all good arc lines (Å)
WAVE SPAN MED	Median wavelength solution span
WAVE SPAN RMS	RMS of wavelength solution span
WAVE SPAN MIN	Minimum wavelength solution span
WAVE SPAN MINSPC	Fibre with minimum wavelength solution span
WAVE SPAN MAX	Maximum wavelength solution span
WAVE SPAN MAXSPC	Fibre with maximum wavelength solution span
WAVE LINES MIN	Minimum number of lines in a wavelength solution
WAVE LINES MINSPC	Fibre with minimum number of lines
WAVE LINES MAX	Maximum number of lines in a wavelength solution
WAVE LINES MAXSPC	Fibre with maximum number of lines
WAVE LINES MED	Median number of lines in a wavelength solution
WAVE RMS MIN	Minimum RMS of a fibre wavelength solution (Å)
WAVE RMS MINSPC	Spectrum with minimum RMS
WAVE RMS MAX	Maximum RMS of a fibre wavelength solution (Å)
WAVE RMS MAXSPC	Spectrum with maximum RMS
WAVE RMS MED	Median RMS of a fibre wavelength solution (Å)
WAVE OFFSET MED	Median wavelength offset compared to reference (Å)
WAVE OFFSET RMS	RMS of wavelength offset compared to reference (Å)
WAVE OFFSET MIN	Minimum wavelength offset compared to reference (Å)
WAVE OFFSET MINSPC	Fibre with minimum wavelength offset
WAVE OFFSET MAX	Maximum wavelength offset compared to reference (Å)
WAVE OFFSET MAXSPC	Fibre with maximum wavelength offset

9.1.5 Parameters

Parameter	Default	Description
level	1	Reduction level (0: quick; 1: normal).
keep	FALSE	Save optional processed / diagnostic products.
ccdproc.swapx	100010101	Flip x axis to correct wavelength direction per arm.
imcombine.combtype	1	Stacking method (1: mean; 2: median).
imcombine.scaletype	0	Stacking scaling method (1: add; 2: mul; 3: dark; 0: none).
imcombine.xrej	FALSE	Do extra rejection cycle in stacking.
imcombine.thresh	5.0	Rejection threshold in terms of background noise when stacking.
scattered.enable	TRUE	Enable scattered light removal.

scattered.nbsize	256	Size of scattered light smoothing cells (pix).
extract.width	5	Spectral extraction aperture (pix).
arc.detthr	-1.0	Detection threshold to find emission features.
arc.nord	-1	Wavelength polynomial fit order.
arc.matchwindow	1.5	Match window for identifying arc lines (Å at 6000Å).
arc.matchgrid	-1.0	Grid search window for identifying arc lines (Å).
fpe.prescoef	0.34	FPE vacuum pressure correction (km/s/mbar).
reference	FALSE	Emit reference rather than master frame.

9.2 qmost_bias_combine

Process a set of bias frames to form a master bias. The input exposures are prescan corrected, trimmed and then stacked. The median and rms background levels are computed in both the prescan region and the light sensitive part of the detector.

Optionally, the generated master calibration can be compared to a reference to look for statistical or spatial variations in the bias.

9.2.1 Input

Input DO.CATG	Optional?	Short description
BIAS	Required	Raw bias frames
MASTER_BPM	Optional	Master bad pixel mask
REFERENCE_BIAS	Optional	Reference bias frame

9.2.2 Output

Output PRO.CATG	Condition	Short description
MASTER_BIAS	`reference=FALSE`	Master bias frame
REFERENCE_BIAS	`reference=TRUE`	Reference bias frame
DIFFIMG_BIAS	Reference given	Bias comparison difference image

9.2.3 Quality control

QC keyword	Description
NUM SAT	Number of saturated pixels
OS MED AMPn	Median bias level in prescan region (ADU)
OS RMS AMPn	RMS of bias level in prescan region (ADU)
IMCOMBINE NUM INPUTS	Number of input frames
IMCOMBINE NUM COMBINED	Number of frames combined
IMCOMBINE MEAN	Mean background level in images that were stacked (ADU)

IMCOMBINE RMS	RMS of background levels in images that were stacked (ADU)
IMCOMBINE MIN	Minimum background level in images that were stacked (ADU)
IMCOMBINE MAX	Maximum background level in images that were stacked (ADU)
IMCOMBINE NOISE MEAN	Mean noise level in images that were stacked (ADU)
IMCOMBINE NUM REJECTED	Total number of rejected pixels in stacking
COMPARE MED	Median of the difference image (ADU)
COMPARE RMS	RMS of the difference image (ADU)
COMPARE BIN MEAN	Mean of binned comparison to reference (ADU)
COMPARE BIN RMS	RMS of binned comparison to reference (ADU)
COMPARE BIN MIN	Lowest bin in comparison to reference (ADU)
COMPARE BIN MAX	Highest bin in comparison to reference (ADU)

9.2.4 Parameters

Parameter	Default	Description
imcombine.combtype	1	Stacking method (1: mean; 2: median).
imcombine.scaletype	1	Stacking scaling method (1: add; 2: mul; 3: dark; 0: none).
imcombine.xrej	FALSE	Do extra rejection cycle in stacking.
imcombine.thresh	5.0	Rejection threshold in terms of background noise when stacking.
diffimg.ncells	256	Number of smoothing cells for comparison statistics.
reference	FALSE	Emit reference rather than master frame.

9.3 qmost_dark_combine

Debias, trim and combine a series of dark frames. Calculate the median and rms of the DC dark current level on the detector.

Optionally, the generated master calibration can be compared to a reference to look for statistical or spatial variations in the dark current.

9.3.1 Input

Input DO.CATG	Optional?	Short description
DARK	Required	Raw dark frames
MASTER_BIAS	Optional	Master bias frame
MASTER_BPM	Optional	Master bad pixel mask
REFERENCE_DARK	Optional	Reference dark frame

9.3.2 Output

Output PRO.CATG	Condition	Short description

MASTER_DARK	`reference=FALSE`	Master dark frame
REFERENCE_DARK	`reference=TRUE`	Reference dark frame
DIFFIMG_DARK	Reference given	Dark comparison difference image

9.3.3 Quality control

QC keyword	Description
NUM SAT	Number of saturated pixels
OS MED AMPn	Median bias level in prescan region (ADU)
OS RMS AMPn	RMS of bias level in prescan region (ADU)
IMCOMBINE NUM INPUTS	Number of input frames
IMCOMBINE NUM COMBINED	Number of frames combined
IMCOMBINE MEAN	Mean background level in images that were stacked (ADU)
IMCOMBINE RMS	RMS of background levels in images that were stacked (ADU)
IMCOMBINE MIN	Minimum background level in images that were stacked (ADU)
IMCOMBINE MAX	Maximum background level in images that were stacked (ADU)
IMCOMBINE NOISE MEAN	Mean noise level in images that were stacked (ADU)
IMCOMBINE NUM REJECTED	Total number of rejected pixels in stacking
COMPARE MED	Median of the difference image (ADU)
COMPARE RMS	RMS of the difference image (ADU)
COMPARE BIN MEAN	Mean of binned comparison to reference (ADU)
COMPARE BIN RMS	RMS of binned comparison to reference (ADU)
COMPARE BIN MIN	Lowest bin in comparison to reference (ADU)
COMPARE BIN MAX	Highest bin in comparison to reference (ADU)

9.3.4 Parameters

Parameter	Default	Description
imcombine.combtype	1	Stacking method (1: mean; 2: median).
imcombine.scaletype	3	Stacking scaling method (1: add; 2: mul; 3: dark; 0: none).
imcombine.xrej	FALSE	Do extra rejection cycle in stacking.
imcombine.thresh	5.0	Rejection threshold in terms of background noise when stacking.
diffimg.ncells	256	Number of smoothing cells for comparison statistics.
reference	FALSE	Emit reference rather than master frame.

9.4 qmost_detector_flat_analyse

Process a set of detector flats to form a master detector flat. The input exposures are prescan corrected, trimmed, bias, and dark corrected. The resulting processed frames are combined to form a master detector flat. Ratios of the count levels in the overlap regions along the amp boundaries are used to determine the relative gains of the amps and apply a gain correction to remove discontinuities at the amp boundaries. The resulting now contiguous image is then filtered using 2D median and boxcar filters to remove the strong illumination pattern cast by the LEDs to obtain a flat suitable for correcting pixel to pixel sensitivity variations. The gain correction is then applied in reverse to the resulting flat to obtain a final detector flat that applies both the gain correction and the pixel to pixel flat field correction.

Optionally, the detector flat can be compared to a reference to look for statistical or spatial variations. This is done prior to filtering using the unfiltered detector flat output so the comparison is sensitive to any variations in the illumination pattern.

9.4.1 Input

Input DO.CATG	Optional?	Short description
DETECTOR_FLAT	Required	Raw LED detector flat frames
MASTER_BIAS	Optional	Master bias frame
MASTER_DARK	Optional	Master dark frame
MASTER_BPM	Optional	Master bad pixel mask
REFERENCE_DETECTOR_FLAT	Optional	Reference detector flat

9.4.2 Output

Output PRO.CATG	Condition	Short description
MASTER_DETECTOR_FLAT	Always	Master detector flat
UNFILTERED_DETECTOR_FLAT	`reference=FALSE`	Unfiltered detector flat
REFERENCE_DETECTOR_FLAT	`reference=TRUE`	Reference detector flat
DIFFIMG_DETECTOR_FLAT	Reference given	Flat comparison ratio image

9.4.3 Quality control

QC keyword	Description
NUM SAT	Number of saturated pixels
OS MED AMPn	Median bias level in prescan region (ADU)
OS RMS AMPn	RMS of bias level in prescan region (ADU)
IMCOMBINE NUM INPUTS	Number of input frames
IMCOMBINE NUM COMBINED	Number of frames combined
IMCOMBINE MEAN	Mean background level in images that were stacked (ADU)
IMCOMBINE RMS	RMS of background levels in images that were stacked (ADU)
IMCOMBINE MIN	Minimum background level in images that were stacked (ADU)
IMCOMBINE MAX	Maximum background level in images that were stacked (ADU)
IMCOMBINE NOISE MEAN	Mean noise level in images that were stacked (ADU)
IMCOMBINE NUM REJECTED	Total number of rejected pixels in stacking
COMPARE MED	Median of the difference image (ADU)
COMPARE RMS	RMS of the difference image (ADU)
COMPARE BIN MEAN	Mean of binned comparison to reference (ADU)

COMPARE BIN RMS	RMS of binned comparison to reference (ADU)
COMPARE BIN MIN	Lowest bin in comparison to reference (ADU)
COMPARE BIN MAX	Highest bin in comparison to reference (ADU)

9.4.4 Parameters

Parameter	Default	Description
imcombine.combtype	1	Stacking method (1: mean; 2: median).
imcombine.scaletype	2	Stacking scaling method (1: add; 2: mul; 3: dark; 0: none).
imcombine.xrej	FALSE	Do extra rejection cycle in stacking.
imcombine.thresh	5.0	Rejection threshold in terms of background noise when stacking.
gaincor.window	16	Measurement strip size for gain correction (pix).
detflat.medfil	25	2D median filter window for removing illumination pattern (pix)
detflat.linfil	5	2D boxcar filter window for removing illumination pattern (pix)
diffimg.ncells	256	Number of smoothing cells for comparison statistics.
reference	FALSE	Emit reference rather than master frame.

9.5 qmost_detector_noise

Use a pair of bias frames and a pair of detector flat frames to measure the detector gain and readout noise. Record the results in a readgain file.

9.5.1 Input

Input DO.CATG	Optional?	Short description
DETECTOR_FLAT	Required	Raw LED detector flat frames (2 required)
BIAS	Optional	Raw bias frames (2)
MASTER_BPM	Optional	Master bad pixel mask

9.5.2 Output

Output PRO.CATG	Condition	Short description
READGAIN	Always	Readgain file

9.5.3 Quality control

QC keyword	Description

BIAS MED AMPn	Median bias level (ADU)
BIAS DIFF AMPn	Median bias difference (ADU)
FLAT MED AMPn	Median bias corrected flat level (ADU)
FLAT DIFF AMPn	Median flat difference (ADU)
CONAD AMPn	Amplifier gain (e-/adu)
READNOISE AMPn	Readout noise (e-)

9.5.4 Parameters

None

9.6 qmost_fibre_flat_analyse

Combine individual fibre flat images into master, OB or sky fibre flat. Extract the fibre flat spectra and normalise them so the ensemble average of each spectrum is unity.

This recipe has 3 modes depending on the type of input given. We give a separate input and output table for each below.

9.6.1 Input and output for daytime facility fibre flat

Input DO.CATG	Optional?	Short description
FIBRE_FLAT_DAY	Required	Raw daytime fibre flat frames
MASTER_BIAS	Optional	Master bias
MASTER_DARK	Optional	Master dark
MASTER_DETECTOR_FLAT	Optional	Master detector flat
MASTER_BPM	Optional	Master bad pixel mask
LINEARITY	Optional	Master linearity table
FIBRE_TRACE	Required	Master fibre trace
FIBRE_MASK	Required	Master fibre mask
MASTER_PSF	Required	Master PSF
MASTER_WAVE	Required	Master wavelength solution

Output PRO.CATG	Condition	Short description
MASTER_FIBRE_FLAT	Always	Master fibre flat
PROC_FIBRE_FLAT	`keep=TRUE`	Processed, stacked 2D image
COSMIC_RAY_MASK	`keep=TRUE` and `level=1`	Cosmic ray mask
EXTRACTED_FIBRE_FLAT	`keep=TRUE`	Extracted fibre flat spectrum

9.6.2 Input and output for night-time OB-level attached fibre flat

Input DO.CATG	Optional?	Short description
FIBRE_FLAT_NIGHT	Required	Raw OB-level attached fibre flat frame
MASTER_BIAS	Optional	Master bias
MASTER_DARK	Optional	Master dark
MASTER_DETECTOR_FLAT	Optional	Master detector flat
MASTER_BPM	Optional	Master bad pixel mask
LINEARITY	Optional	Master linearity table
FIBRE_TRACE	Required	Fibre trace
FIBRE_MASK	Required	Fibre mask
MASTER_PSF	Required	Master PSF
MASTER_WAVE	Required	Master wavelength solution
MASTER_FIBRE_FLAT	Required	Master fibre flat

Output PRO.CATG	Condition	Short description
OB_FIBRE_FLAT	Always	OB fibre flat
PROC_FIBRE_FLAT	`keep=TRUE`	Processed, stacked 2D image
COSMIC_RAY_MASK	`keep=TRUE` and `level=1`	Cosmic ray mask
EXTRACTED_FIBRE_FLAT	`keep=TRUE`	Extracted fibre flat spectrum

9.6.3 Input and output for twilight sky fibre flat

Input DO.CATG	Optional?	Short description
FIBRE_FLAT_SKY	Required	Raw twilight sky fibre flat frames
MASTER_BIAS	Optional	Master bias
MASTER_DARK	Optional	Master dark
MASTER_DETECTOR_FLAT	Optional	Master detector flat
MASTER_BPM	Optional	Master bad pixel mask
LINEARITY	Optional	Master linearity table
FIBRE_TRACE	Required	Fibre trace
FIBRE_MASK	Required	Fibre mask
MASTER_PSF	Required	Master PSF
MASTER_WAVE	Required	Master wavelength solution
MASTER_FIBRE_FLAT	Required	Master fibre flat

Output PRO.CATG	Condition	Short description
SKY_FIBRE_FLAT	Always	Sky fibre flat
PROC_FIBRE_FLAT	`keep=TRUE`	Processed, stacked 2D image
COSMIC_RAY_MASK	`keep=TRUE` and `level=1`	Cosmic ray mask
EXTRACTED_FIBRE_FLAT	`keep=TRUE`	Extracted fibre flat spectrum

9.6.4 Quality control

QC keyword	Description
NUM SAT	Number of saturated pixels
OS MED AMPn	Median bias level in prescan region (ADU)
OS RMS AMPn	RMS of bias level in prescan region (ADU)
IMCOMBINE MEAN	Mean background level in images that were stacked (ADU)
IMCOMBINE RMS	RMS of background levels in images that were stacked (ADU)
IMCOMBINE MIN	Minimum background level in images that were stacked (ADU)
IMCOMBINE MAX	Maximum background level in images that were stacked (ADU)
IMCOMBINE NOISE MEAN	Mean noise level in images that were stacked (ADU)
IMCOMBINE NUM COMBINED	Number of frames combined
IMCOMBINE NUM INPUTS	Number of input frames
IMCOMBINE NUM REJECTED	Total number of rejected pixels in stacking
EXT FLUX MED	Median of extracted counts over fibres (ADU)
EXT FLUX RMS	RMS of extracted counts over fibres (ADU)
EXT FLUX MIN	Minimum extracted counts over fibres (ADU)
EXT FLUX MINSPC	Fibre with minimum extracted counts
EXT FLUX MAX	Maximum extracted counts over fibres (ADU)
EXT FLUX MAXSPC	Fibre with maximum extracted counts
EXT SN MED	Median SNR over fibres
EXT SN RMS	RMS of SNR over fibres
EXT SN MIN	Minimum SNR over fibres
EXT SN MINSPC	Fibre with minimum SNR
EXT SN MAX	Maximum SNR over fibres
EXT SN MAXSPC	Fibre with maximum SNR
SCATTL MED	Median scattered light (ADU)
SCATTL RMS	RMS of scattered light (ADU)
SCATTL RESID MED	Median scattered light residual (ADU)
SCATTL RESID RMS	RMS of scattered light residual (ADU)
FIBFLAT ENS MED	Ensemble median of fibre fluxes (ADU)
FIBFLAT ENS RMS	RMS of the fibre fluxes (ADU)
FIBFLAT ENS MIN	Minimum fibre flux (ADU)
FIBFLAT ENS MINFIB	Fibre ID of fibre with minimum flux
FIBFLAT ENS MINSPC	Spectrum with minimum flux
FIBFLAT ENS MAX	Maximum fibre flux (ADU)
FIBFLAT ENS MAXFIB	Fibre ID of fibre with maximum flux
FIBFLAT ENS MAXSPC	Spectrum with maximum flux
EXT GOF MED	Median goodness of fit
EXT NUM REJECTED	Number of rejected pixels

9.6.5 Parameters

Parameter	Default	Description
level	1	Reduction level (0: quick; 1: normal).
keep	FALSE	Save optional processed / diagnostic products.

ccdproc.swapx	100010101	Flip x axis to correct wavelength direction per arm.
imcombine.combtype	1	Stacking method (1: mean; 2: median).
imcombine.scaletype	2	Stacking scaling method (1: add; 2: mul; 3: dark; 0: none).
imcombine.xrej	FALSE	Do extra rejection cycle in stacking.
imcombine.thresh	5.0	Rejection threshold in terms of background noise when stacking.
scattered.enable	TRUE	Enable scattered light removal.
scattered.nbsize	256	Size of scattered light smoothing cells (pix).
extract.crosstalk	TRUE	Enable crosstalk correction.
extract.cr_thresh	10.0	Rejection threshold for PSF spectral extraction.
extract.niter	1	Number of rejection iterations in PSF extraction.
extract.width	6	Spectral extraction aperture (pix).
skyflat.underexp	100.0	Minimum counts in ADU for twilight flats.
skyflat.overexp	120000.0	Maximum counts in ADU for twilight flats.
skyflat.rej_thresh	5.0	Threshold for outlier rejection when combining sky flats.
ffnorm.track	TRUE	Remove lamp spectrum (median response at each wavelength).
ffnorm.smooth	51	Fibre flat smoothing box in spectral pixels.
ffnorm.rescale	TRUE	Remove fibre throughput variations by scaling fibres.

9.7 qmost_fpe_analyse

Combine individual simufpe frames, remove scattered light, and do a boxcar extraction. Identify emission features in the extracted spectrum and measure their wavelengths using the given simuarc wavelength solution. Emit FPE line list.

9.7.1 Input

Input DO.CATG	Optional?	Short description
FIBRE_WAVE_SIMUFPE	Required	Raw simufpe frames
MASTER_BIAS	Optional	Master bias
MASTER_DARK	Optional	Master dark
MASTER_DETECTOR_FLAT	Optional	Master detector flat
MASTER_BPM	Optional	Master bad pixel mask
LINEARITY	Optional	Master linearity table
FIBRE_TRACE	Required	Master fibre trace
FIBRE_MASK	Required	Master fibre mask
SIMUARC_WAVE	Required	Simultaneous calibration wavelength solution

9.7.2 Output

Output PRO.CATG	Condition	Short description
FPE_LINELIST	Always	FPE line list
PROC_FIBRE_WAVE	`keep=TRUE`	Processed, stacked 2D image

FPE_SPECTRUM	`keep=TRUE`	Extracted FPE spectrum

9.7.3 Quality control

QC keyword	Description
NUM SAT	Number of saturated pixels
OS MED AMPn	Median bias level in prescan region (ADU)
OS RMS AMPn	RMS of bias level in prescan region (ADU)
IMCOMBINE MEAN	Mean background level in images that were stacked (ADU)
IMCOMBINE RMS	RMS of background levels in images that were stacked (ADU)
IMCOMBINE MIN	Minimum background level in images that were stacked (ADU)
IMCOMBINE MAX	Maximum background level in images that were stacked (ADU)
IMCOMBINE NOISE MEAN	Mean noise level in images that were stacked (ADU)
IMCOMBINE NUM COMBINED	Number of frames combined
IMCOMBINE NUM INPUTS	Number of input frames
IMCOMBINE NUM REJECTED	Total number of rejected pixels in stacking
SCATTL MED	Median scattered light (ADU)
SCATTL RMS	RMS of scattered light (ADU)
SCATTL RESID MED	Median scattered light residual (ADU)
SCATTL RESID RMS	RMS of scattered light residual (ADU)
EXT FLUX MED	Median of extracted counts over fibres (ADU)
EXT FLUX RMS	RMS of extracted counts over fibres (ADU)
EXT FLUX MIN	Minimum extracted counts over fibres (ADU)
EXT FLUX MINSPC	Fibre with minimum extracted counts
EXT FLUX MAX	Maximum extracted counts over fibres (ADU)
EXT FLUX MAXSPC	Fibre with maximum extracted counts
EXT SN MED	Median SNR over fibres
EXT SN RMS	RMS of SNR over fibres
EXT SN MIN	Minimum SNR over fibres
EXT SN MINSPC	Fibre with minimum SNR
EXT SN MAX	Maximum SNR over fibres
EXT SN MAXSPC	Fibre with maximum SNR
FPE NFIB MEAN	Mean number of fibres each FPE line was detected in
FPE NFIB MAX	Maximum number of fibres each FPE line was detected in
FPE RMS MEAN	Mean FPE line RMS (Å)
FPE RMS MIN	Minimum FPE line RMS (Å)
FPE RMS MAX	Maximum FPE line RMS (Å)

9.7.4 Parameters

Parameter	Default	Description
keep	FALSE	Save optional processed / diagnostic products.
ccdproc.swapx	100010101	Flip x axis to correct wavelength direction per arm.

imcombine.combtype	1	Stacking method (1: mean; 2: median).
imcombine.scaletype	0	Stacking scaling method (1: add; 2: mul; 3: dark; 0: none).
imcombine.xrej	FALSE	Do extra rejection cycle in stacking.
imcombine.thresh	5.0	Rejection threshold in terms of background noise when stacking.
scattered.enable	TRUE	Enable scattered light removal.
scattered.nbsize	256	Size of scattered light smoothing cells (pix).
extract.width	5	Spectral extraction aperture (pix).
arc.detthr	-1.0	Detection threshold to find emission features.
arc.matchwindow	1.5	Match window for identifying arc lines (Å at 6000Å).

9.8 qmost_linearity_analyse

Analyse a set of detector flats of a constant light source taken with an exposure time ramp to measure detector linearity. Emit a linearity correction table and a detector bad pixel mask. The linearity ramp exposures can optionally be interleaved with lamp brightness monitoring exposures of fixed exposure time to measure and correct for any variations in lamp brightness.

9.8.1 Input

Input DO.CATG	Optional?	Short description
DETECTOR_FLAT_LIN	Required	Raw linearity ramp detector flats
DETECTOR_FLAT_MON	Optional	Raw monitoring detector flats
MASTER_BIAS	Optional	Master bias frame
MASTER_DARK	Optional	Master dark frame
MASTER_BPM	Optional	Master bad pixel mask

9.8.2 Output

Output PRO.CATG	Condition	Short description
LINEARITY	Always	Linearity table
BPM	Always	Bad pixel mask

9.8.3 Quality control

QC keyword	Description
NUM SAT	Number of saturated pixels
OS MED AMPn	Median bias level in prescan region (ADU)
OS RMS AMPn	RMS of bias level in prescan region (ADU)
DETFLAT MIN	Minimum mean flat level (ADU)
DETFLAT MINFILE	File with minimum mean flat level
DETFLAT MAX	Maximum mean flat level (ADU)

DETFLAT MAXFILE	File with maximum mean flat level
BPM NBAD	Number of bad pixels
BPM BADFRAC	Fraction of bad pixels
LIN NL1K	The mean estimated non-linearity at 1000 ADU (percent)
LIN NL5K	The mean estimated non-linearity at 5000 ADU (percent)
LIN NL10K	The mean estimated non-linearity at 10000 ADU (percent)
LIN NL20K	The mean estimated non-linearity at 20000 ADU (percent)
LIN NL30K	The mean estimated non-linearity at 30000 ADU (percent)
LIN NL40K	The mean estimated non-linearity at 40000 ADU (percent)
LIN NL50K	The mean estimated non-linearity at 50000 ADU (percent)
LIN RMS MEAN	The mean RMS of the linearity fit (ADU)
LIN RMS MIN	The minimum RMS of the linearity fit (ADU)
LIN RMS MINAMP	Amplifier with the minimum RMS of the linearity fit
LIN RMS MAX	The maximum RMS of the linearity fit (ADU)
LIN RMS MAXAMP	Amplifier with the maximum RMS of the linearity fit

9.8.4 Parameters

Parameter	Default	Description
linearity.docorr	TRUE	Use monitor sequence to correct for lamp brightness variations.
linearity.nord	4	Polynomial order for linearity fit.
linearity.niter	3	Number of rejection iterations in polynomial fit.
linearity.clipthr	5.0	The number of sigma for outlier rejection.
linearity.underexp	1000	Minimum count level in ADU to reject underexposed flats.
linearity.overexp	60000	Maximum count level in ADU to reject overexposed flats.
linearity.mingood	5	Minimum number of good images required.
bpm.lthr	8.0	Lower threshold in sigma to flag bad pixels.
bpm.hthr	8.0	Upper threshold in sigma to flag bad pixels.
bpm.badfrac	0.25	[0,1] fraction of exposures to flag pixel as bad.
bpm.nmax	20	The maximum number of flats to use in BPM analysis.

9.9 qmost_psf_analyse

Combine individual fibre flat images into a master fibre flat. Use the master fibre flat to measure the spatial profile at each spectral coordinate along each fibre, and record the results in a 3-dimensional map.

9.9.1 Input

Input DO.CATG	Optional?	Short description
FIBRE_FLAT_DAY	Required	Raw daytime fibre flat frames
MASTER_BIAS	Optional	Master bias
MASTER_DARK	Optional	Master dark

MASTER_DETECTOR_FLAT	Optional	Master detector flat
MASTER_BPM	Optional	Master bad pixel mask
LINEARITY	Optional	Master linearity table
FIBRE_TRACE	Required	Master fibre trace
FIBRE_MASK	Required	Master fibre mask

9.9.2 Output

Output PRO.CATG	Condition	Short description
MASTER_PSF	Always	Master PSF file
PROC_FIBRE_FLAT	`keep=true`	Processed, stacked 2D image

9.9.3 Quality control

QC keyword	Description
NUM SAT	Number of saturated pixels
OS MED AMPn	Median bias level in prescan region (ADU)
OS RMS AMPn	RMS of bias level in prescan region (ADU)
IMCOMBINE MEAN	Mean background level in images that were stacked (ADU)
IMCOMBINE RMS	RMS of background levels in images that were stacked (ADU)
IMCOMBINE MIN	Minimum background level in images that were stacked (ADU)
IMCOMBINE MAX	Maximum background level in images that were stacked (ADU)
IMCOMBINE NOISE MEAN	Mean noise level in images that were stacked (ADU)
IMCOMBINE NUM COMBINED	Number of frames combined
IMCOMBINE NUM INPUTS	Number of input frames
IMCOMBINE NUM REJECTED	Total number of rejected pixels in stacking
SCATTL MED	Median scattered light (ADU)
SCATTL RMS	RMS of scattered light (ADU)
SCATTL RESID MED	Median scattered light residual (ADU)
SCATTL RESID RMS	RMS of scattered light residual (ADU)
PSF FWHM MED	Median PSF FWHM (pix)
PSF FWHM RMS	RMS PSF FWHM (pix)
PSF FWHM MIN	Minimum PSF FWHM (pix)
PSF FWHM MINSPC	Fibre with minimum PSF FWHM
PSF FWHM MAX	Maximum PSF FWHM (pix)
PSF FWHM MAXSPC	Fibre with maximum PSF FWHM
PSF FWHM POS	Spectral pixel where FWHM was evaluated

9.9.4 Parameters

Parameter	Default	Description

keep	FALSE	Save optional processed / diagnostic products.
ccdproc.swapx	100010101	Flip x axis to correct wavelength direction per arm.
imcombine.combtype	1	Stacking method (1: mean; 2: median).
imcombine.scaletype	0	Stacking scaling method (1: add; 2: mul; 3: dark; 0: none).
imcombine.xrej	FALSE	Do extra rejection cycle in stacking.
imcombine.thresh	5.0	Rejection threshold in terms of background noise when stacking.
scattered.enable	TRUE	Enable scattered light removal.
scattered.nbsize	256	Size of scattered light smoothing cells (pix).
psf.hwidth	5	PSF measurement window relative to fibre centre (pix).
psf.subsample	5	Number of PSF samples per spatial pixel.
psf.sblock	100	Number of spectral pixels averaged for PSF measurement.

9.10 qmost_science_process

Raw science images are debiased, trimmed, dark corrected, linearity corrected, and detector flat field corrected. Spectra are then extracted, wavelength calibrated, and flat fielded using fibre flat fields. The resulting spectra are combined with a static sensitivity function and emitted into a 2D "ANCILLARY.MOSSPECTRA" format output file with each row of the 2D image array containing the extracted spectrum for a single fibre. Optionally, the extracted spectra can also be corrected for sky background.

All raw images passed in a single SOF must be from the same OB, and must match in terms of spectrograph and fibre configuration. OB level stacking is supported and will be invoked automatically if multiple raw images are given. These are extracted separately and stacked after spectral extraction, wavelength calibration, fibre flat field correction and sky subtraction (if enabled).

9.10.1 Input

Input DO.CATG	Optional?	Short description
OBJECT	Required	Raw images with science spectra
MASTER_BIAS	Optional	Master bias
MASTER_DARK	Optional	Master dark
MASTER_DETECTOR_FLAT	Optional	Master detector flat
MASTER_BPM	Optional	Master bad pixel mask
LINEARITY	Optional	Master linearity table
FIBRE_TRACE	Required	Fibre trace
FIBRE_MASK	Required	Fibre mask
MASTER_PSF	Required	Master PSF
MASTER_WAVE	Required	Master wavelength solution
OB_WAVE	Optional	OB-level wavelength correction
MASTER_FIBRE_FLAT	Optional	Master fibre flat
OB_FIBRE_FLAT	Optional	OB-level fibre flat
SKY_FIBRE_FLAT	Optional	Twilight sky fibre flat
SENSITIVITY	Optional	Sensitivity function

9.10.2 Output

Output PRO.CATG	Condition	Short description
SCIENCE	Always	Extracted spectra
PROC_SCIENCE	`keep=true`	Processed 2D image
UNCALIBRATED_SCIENCE	`keep=true`	Uncalibrated extracted spectra
COSMIC_RAY_MASK	`keep=true` and `level=1`	Cosmic ray mask
EIGEN	`keep=true` and `skysub.enable`	Sky eigenvectors
SKY	`keep=true` and `skysub.enable`	Sky diagnostics file

9.10.3 Quality control

QC keyword	Description
NUM SAT	Number of saturated pixels
OS MED AMPn	Median bias level in prescan region (ADU)
OS RMS AMPn	RMS of bias level in prescan region (ADU)
EXT FLUX MED	Median of extracted counts over fibres (ADU)
EXT FLUX RMS	RMS of extracted counts over fibres (ADU)
EXT FLUX MIN	Minimum extracted counts over fibres (ADU)
EXT FLUX MINSPC	Fibre with minimum extracted counts
EXT FLUX MAX	Maximum extracted counts over fibres (ADU)
EXT FLUX MAXSPC	Fibre with maximum extracted counts
EXT SN MED	Median SNR over fibres
EXT SN RMS	RMS of SNR over fibres
EXT SN MIN	Minimum SNR over fibres
EXT SN MINSPC	Fibre with minimum SNR
EXT SN MAX	Maximum SNR over fibres
EXT SN MAXSPC	Fibre with maximum SNR
SCATTL MED	Median scattered light (ADU)
SCATTL RMS	RMS of scattered light (ADU)
SCATTL RESID MED	Median scattered light residual (ADU)
SCATTL RESID RMS	RMS of scattered light residual (ADU)
EXT GOF MED	Median goodness of fit
EXT NUM REJECTED	Number of rejected pixels
SKY CONT MED	Median sky continuum level (ADU)
SKY CONT RMS	RMS variation in sky level (ADU)
SKY NUM	Number of skies found
SKY NUSED	Number of skies used
SKY RESID MED	Median normalised sky line residual
SKY RESID RMS	RMS normalised sky line residual
ZMAG MED	Median magnitude zero point (mag)
ZMAG NUM	Number of magnitudes used
ZMAG RMS	RMS magnitude zero point (mag)

9.10.4 Parameters

Parameter	Default	Description
level	1	Reduction level (0: quick; 1: normal).
keep	FALSE	Save optional processed / diagnostic products.
ccdproc.swapx	100010101	Flip x axis to correct wavelength direction per arm.
scattered.enable	TRUE	Enable scattered light removal.
scattered.nbsize	256	Size of scattered light smoothing cells (pix).
extract.crosstalk	TRUE	Enable crosstalk correction.
extract.cr_thresh	5.0	Rejection threshold for PSF spectral extraction.
extract.niter	3	Number of rejection iterations in PSF extraction.
extract.width	6	Spectral extraction aperture (pix).
skysub.enable	-1	1: enable sky subtraction. -1: use level parameter value.
skysub.neigen	-1	Maximum number of eigenvectors for sky PCA.
skysub.smoothing	50	Spectral smoothing window to determine sky continuum (Å).
combine.rej_thresh	5.0	Threshold for outlier rejection when stacking spectra.

9.11 qmost_trace

Combine individual fibre flat images into master fibre flat. Trace each of the fibre profiles along the dispersion axis. Use the trace to define the location of blank parts of the detector for use in modelling the scattered light.

9.11.1 Input

Note: any of the three types of fibre flat frame can be used.

Input DO.CATG	Optional?	Short description
FIBRE_FLAT_DAY	Required	Raw daytime fibre flat frames
or		
FIBRE_FLAT_NIGHT		Raw OB-level attached fibre flat frame
or		
FIBRE_FLAT_SKY		Raw twilight sky fibre flat frames
MASTER_BIAS	Optional	Master bias
MASTER_DARK	Optional	Master dark
MASTER_DETECTOR_FLAT	Optional	Master detector flat
MASTER_BPM	Optional	Master bad pixel mask
LINEARITY	Optional	Master linearity table
SLIT_MASK	Required	Master slit mask
REFERENCE_FIBRE_TRACE	Optional	Reference trace table

9.11.2 Output

Output PRO.CATG	Condition	Short description
FIBRE_TRACE	Always	Trace table
FIBRE_MASK	Always	Fibre mask
PROC_FIBRE_FLAT	`keep=true`	Processed, stacked 2D image

9.11.3 Quality control

QC keyword	Description
NUM SAT	Number of saturated pixels
OS MED AMPn	Median bias level in prescan region (ADU)
OS RMS AMPn	RMS of bias level in prescan region (ADU)
IMCOMBINE MEAN	Mean background level in images that were stacked (ADU)
IMCOMBINE RMS	RMS of background levels in images that were stacked (ADU)
IMCOMBINE MIN	Minimum background level in images that were stacked (ADU)
IMCOMBINE MAX	Maximum background level in images that were stacked (ADU)
IMCOMBINE NOISE MEAN	Mean noise level in images that were stacked (ADU)
IMCOMBINE NUM COMBINED	Number of frames combined
IMCOMBINE NUM INPUTS	Number of input frames
IMCOMBINE NUM REJECTED	Total number of rejected pixels in stacking
EXT FLUX MED	Median of extracted counts over fibres (ADU)
EXT FLUX RMS	RMS of extracted counts over fibres (ADU)
EXT FLUX MIN	Minimum extracted counts over fibres (ADU)
EXT FLUX MINSPC	Fibre with minimum extracted counts
EXT FLUX MAX	Maximum extracted counts over fibres (ADU)
EXT FLUX MAXSPC	Fibre with maximum extracted counts
EXT SN MED	Median SNR over fibres
EXT SN RMS	RMS of SNR over fibres
EXT SN MIN	Minimum SNR over fibres
EXT SN MINSPC	Fibre with minimum SNR
EXT SN MAX	Maximum SNR over fibres
EXT SN MAXSPC	Fibre with maximum SNR
SCATTL MED	Median scattered light (ADU)
SCATTL RMS	RMS of scattered light (ADU)
SCATTL RESID MED	Median scattered light residual (ADU)
SCATTL RESID RMS	RMS of scattered light residual (ADU)
TRACE RMS MED	Average RMS of trace fits (pix)
TRACE RMS MIN	Minimum RMS of trace fits (pix)
TRACE RMS MINSPC	Fibre with minimum RMS of trace fit
TRACE RMS MAX	Maximum RMS of trace fits (pix)
TRACE RMS MAXSPC	Fibre with maximum RMS of trace fit
TRACE FWHM MED	Median FWHM of spatial profiles (pix)
TRACE FWHM RMS	RMS of FWHM of spatial profiles (pix)
TRACE CONTRAST MEAN	Average trace peak to trough contrast

TRACE CONTRAST RMS	RMS trace peak to trough contrast
TRACE CONTRAST MIN	Minimum trace peak to trough contrast
TRACE CONTRAST MINSPC	Fibre with minimum trace contrast
TRACE CONTRAST MAX	Maximum trace peak to trough contrast
TRACE CONTRAST MAXSPC	Fibre with maximum trace contrast
TRACE GAP MEAN	Mean fibre spacing within slitlet (pix)
TRACE GAP RMS	RMS fibre spacing within slitlet (pix)
TRACE GAP MIN	Minimum fibre spacing within slitlet (pix)
TRACE GAP MAX	Maximum fibre spacing within slitlet (pix)
SLITLET GAP MEAN	Mean slitlet spacing (pix)
SLITLET GAP RMS	RMS slitlet spacing (pix)
SLITLET GAP MIN	Minimum slitlet spacing (pix)
SLITLET GAP MAX	Maximum slitlet spacing (pix)
TRACE NUM FIBRES	Number of fibres detected and traced
TRACE OFFSET MED	Median trace offset compared to reference (pix)
TRACE OFFSET RMS	RMS of trace offset compared to reference (pix)
TRACE OFFSET MIN	Minimum trace offset compared to reference (pix)
TRACE OFFSET MINSPC	Fibre with minimum trace offset
TRACE OFFSET MAX	Maximum trace offset compared to reference (pix)
TRACE OFFSET MAXSPC	Fibre with maximum trace offset

9.11.4 Parameters

Parameter	Default	Description
level	1	Reduction level (0: quick; 1: normal).
keep	FALSE	Save optional processed / diagnostic products.
ccdproc.swapx	100010101	Flip x axis to correct wavelength direction per arm.
imcombine.combtype	1	Stacking method (1: mean; 2: median).
imcombine.scaletype	0	Stacking scaling method (1: add; 2: mul; 3: dark; 0: none).
imcombine.xrej	FALSE	Do extra rejection cycle in stacking.
imcombine.thresh	5.0	Rejection threshold in terms of background noise when stacking.
scattered.enable	TRUE	Enable scattered light removal.
scattered.nbsize	256	Size of scattered light smoothing cells (pix).
trace.iblock	48	Number of spectral pixels averaged for trace.
trace.detthr	5.0	Detection threshold (SNR) to locate fibre images.
trace.nord	7	Polynomial degree for trace fit.
trace.startline	-1	Spectral pixel to start tracing (-1: use centre of detector).
trace.width	6	Width of a single fibre profile (pix).
extract.width	5	Spectral extraction aperture (pix).

10 Algorithms

10.1 General Algorithms

This section provides a high-level overview of the pipeline algorithms, and information about the parameters available at recipe level. The pipeline design document VIS-DER-4MOST-47110-1410-0002 "QC and Level-1 Science Data Reduction Pipeline Description" provides a more detailed description of the implementation of these functions in the data reduction library.

10.1.1 Basic 2D image reduction (removal of detector signature)

The 2D image reduction steps performed are, in order:

- Optionally, linearity correction can be carried out at this stage (before bias).
- Prescan correction using the prescan region of each amplifier to determine prescan level and noise. The prescan level is determined by histogramming the image raw pixels and using the histogram to compute the median and a robust (MAD-based) estimator of the standard deviation of the image pixels to sub-ADU precision. The measured prescan level is then subtracted from the pixels of the amplifier.
- Trimming to remove the non-illuminated regions of the detector and stitching into a single contiguous image.
- 2D bias correction to remove any residual 2-D bias non-uniformity not removed by prescan correction.
- Optionally, linearity correction can be carried out at this stage (after bias).
- Calculation of the variance array:

  $$\mathrm{var}(x,y) = g^2\ \mathrm{RON}^2 + g \begin{cases} 0, & \mathrm{raw}(x,y) < 0 \\ \mathrm{raw}(x,y), & \mathrm{raw}(x,y) \geq 0 \end{cases} \tag{8}$$

  where g is the detector gain in ADU/electron and RON is read noise in electrons.

  The variance of the master bias is also added, if used.
- Dark correction, using a master dark frame scaled by the relative exposure times of the image being processed to the master dark frame. The variance of the scaled master dark is also added to the variance array.
- Division by the detector flat field. Due to the way the detector flat field frame is made, this also corrects gain differences between the amplifiers. Pixels with a value of zero in the detector flat are flagged as bad. The flat variance is propagated according to the standard Gaussian error propagation formula applied to the detector flat correction:

  $$o_j = \frac{i_j}{f_j} \tag{9}$$

$$\mathrm{var}(o_j) = o_j^2 \left[\frac{\mathrm{var}(i_j)}{i_j^2} + \frac{\mathrm{var}(f_j)}{f_j^2} \right] = \frac{\mathrm{var}(i_j)}{f_j^2} + o_j^2 \frac{\mathrm{var}(f_j)}{f_j^2} \tag{10}$$

where o_j is the jth output pixel, i_j is the input pixel, and f_j is the normalised flat pixel.

- Axis-flipping the images to produce a consistent orientation of the spectral and spatial axes suitable for spectroscopic processing.

10.1.2 2D image combination (stacking)

A general purpose 2D image combination routine is implemented for stacking detector calibration and spectroscopic calibration images at the 2D level, applied immediately after basic 2D image reduction. This can be done using clipped mean or median estimators, depending on the value of the parameter `imcombine.combtype`, where a value of 1 selects mean and 2 selects median.

The background in each image is adjusted based on the value of the parameter `imcombine.scaletype` to bring the images onto a common system prior to averaging. The following scaletype values are supported:

Value	Description	Equation
0	No scaling	images[i]
1	Additive	images[i] + ⟨background⟩ − background[i]
2	Multiplicative	images[i] × ⟨background⟩/background[i]
3	Dark frame	(images[i] − background[i]) × exptime[0]/exptime[i] + ⟨background⟩

where in the table we give an equation for the quantity that is the input to the averaging for image i. The array quantity images denotes the pixel of the input image, background is the measured average background level of the image, and exptime is the exposure time. Angle brackets denote the average over all of the images. Mode 1 is intended for bias frames where any additive background offsets are removed, mode 2 is intended for detector or fibre flat frames where any variations in light level as judged by the ratio of the background levels are removed, and mode 3 is intended for dark frames and extends mode 1 by also normalising the frames to an equal exposure time. The multiplicative adjustments in modes 2 and 3 are also applied to the variance by multiplying it by the square of the factor applied to the image.

The background level is determined by histogramming the (nearly integer) image pixels and using the histogram to compute the median and a robust (MAD-based) estimator of the standard deviation of the image pixels to sub-ADU precision. A further specialisation to processing fibre spectra is enabled when processing spectroscopic frames, where an initial histogram is used to determine the 90th percentile of the distribution of image pixel intensities, and the background level calculation then considers only those pixels brighter than this limit, i.e. the brightest 10% of the image pixels. This provides a simple means to discard the unilluminated pixels without having to use a fibre mask, which may not yet be available.

Following the background adjustments, the requested average is applied. The choices are an iterative, clipped median or an iterative, clipped mean. In both cases, the clipping used for outlier rejection is a variant of kappa sigma clipping with a threshold thresh × sigma specified by the argument `imcombine.thresh`. The appropriate value of sigma is the larger of the average background noise or the individual pixel standard deviation calculated from the variance array for the input image (not less than 1.0 ADU). The exact manner in which this clipping is applied depends on the requested type of average, which we now describe separately for each of the options.

If `imcombine.combtype == 1`, mean combination is used. For each output pixel, the mean of the corresponding pixels in the N input frames is computed. Up to $N - 1$ iterations of outlier rejection then commence. Within each of these iterations, the residual (absolute deviation from the mean) is computed for each of the remaining frames that have not already been rejected, and the frame with the largest residual above thresh $\times$ sigma (see above) is rejected and the mean recomputed excluding it. This process continues until no more frames remain with residuals above thresh $\times$ sigma.

Following this rejection process, the variance in the final mean is computed as:

$$\mathrm{var(out)} = \frac{1}{N_{\mathrm{good}}^2} \sum_{i=1}^{N_{\mathrm{good}}} \mathrm{var}(i) \tag{11}$$

where N_{good} is the number of frames remaining after rejection.

If `imcombine.combtype == 2`, median combination is used. For each output pixel, the corresponding pixels in the input frames are retrieved and sorted in order of ADU value. The median value is then computed, using the average of the two middle frames if the number of frames N is even. If it is odd, the median frame itself is used if the number of frames is ≤ 5, otherwise a $1:2:1$ weighted average that includes the two frames either side of the median frame is used to reduce noise. Up to $N/2$, if $N > 5$, otherwise 1, of the top frames in the sorted list are then rejected if they have residuals (value – median) above thresh $\times$ sigma (see above). Note that this only clips upward outliers (e.g. cosmics), the median is presumed robust enough to deal with any downward outliers itself. If any frames were rejected, the median is recalculated. Finally, to propagate the variance, the variances of the pixels used in the median are retrieved, and the output variance computed as:

$$\mathrm{var(out)} = \frac{\pi}{2N_{\mathrm{good}}^2} \sum_{i=1}^{N_{\mathrm{good}}} \mathrm{var}(i) \tag{12}$$

where N_{good} is the number of frames remaining after rejection. The factor of $\pi/2$ is the square of the usual result for the ratio of the standard error in the median to standard error in the mean for a Gaussian distribution.

Following the combination, an optional extra clipping stage can be requested by setting `imcombine.xrej` to true. This is not normally used in 4MOST, but we describe it here briefly for completeness. The residual images corresponding to each input frame are computed, based on applying the adjustments given above based on the scaletype parameter in reverse to adjust the output image onto the system of the input image and then taking the difference. These residual images are used to recompute the individual background noise estimates using the same sky level calculation as described above, where the residual images should now be free of any common features that appear in the stacks, and thus contain only noise. Based on these revised noise estimates, the combination process is then repeated, but now using these noise estimates as sigma when doing the kappa sigma clipping.

10.1.3 Measurement of read noise and gain

The read noise and gain are measured using two LED flats of similar illumination and, optionally, two bias frames. If the pair of bias frames are not available, the prescan / overscan regions of the LED flats are used instead. Since the gain and readout noise of each amplifier are different, this done on a per-amplifier basis

Forming the difference of the two flat frames then gives a variance for the difference image σ_f^2. Doing the same for the two bias regions yields a variance σ_b^2 . If the background levels of the flat and bias frames are respectively m_{f1}, m_{f2} and m_{b1}, m_{b2}, then the conversion factor in electrons per ADU is:

$$\epsilon = \left[(m_{f1} + m_{f2}) - (m_{b1} + m_{b2})\right] / (\sigma_f^2 - \sigma_b^2) \tag{13}$$

and the read noise in electrons is:

$$\sigma_{\mathrm{RON}} = \epsilon \, \sigma_b / \sqrt{2} \tag{14}$$

In ESO parlance, gain is the reciprocal of conversion factor (CONAD), but this definition is non-standard in astronomy and can result in confusion. In the present document, we have stated the units to disambiguate wherever there could be ambiguity in the meaning of the word “gain”.

The background levels and variances are determined by histogramming the integer raw image pixels and using the histogram to compute the median and a robust (MAD-based) estimator of the standard deviation of the image pixels to sub-ADU precision. This is done on the appropriate sum and difference images to form the quantities needed to evaluate the equations above.

10.1.4 Bad pixel mask definition

The detector flat images from a linearity sequence are first combined as described in section 10.1.2 with multiplicative scaling to produce a master detector flat. Each individual input detector flat is then divided by this master detector flat to form a ratio image, and the median and $\sigma = 1.48 \times \mathrm{MAD}$ of the ratio image are computed. The ratio image should exhibit an almost uniform background DC level. Pixels in a ratio image that fall by a threshold amount above or below that DC level can be marked. Pixels that consistently fail in this way are then marked in a bad pixel mask. Those that only fail occasionally for being too high are likely due to cosmic ray hits and should be ignored.

Pixels with value p satisfying:

$$\mathrm{median} - \texttt{bpm.lthr}\,\sigma \leq p \leq \mathrm{median} + \texttt{bpm.hthr}\,\sigma \tag{15}$$

are considered good. For each pixel on the detector, a count is maintained of how many times (i.e. on how many frames) each detector pixel failed this criterion resulting in a 2D integer image containing these counts.

The bad pixel mask is then created by thresholding the 2D integer image created in the previous step. The threshold used is `bpm.badfrac` $\times N$ where N is the number of flat frames given, but not less than 2, rounded to nearest integer. Any pixel with count greater than or equal to this threshold is flagged as bad by setting it to true in the bad pixel mask.

10.1.5 Non-linearity measurement

A special set of detector flats are gathered in a "linearity ramp" of exposure times, where the exposure times are set so the average counts evenly span the full dynamic range of the detector from the bias level up to saturation. The ramp flats can optionally be interspersed with detector flats of a fixed exposure time used to monitor lamp brightness, but this is not usually done for 4MOST since the LEDs used for detector flat illumination are relatively stable.

The median flux in the linearity flat sequence observations (corrected for drift, if `linearity.docorr` is true) computed on a per-amplifier basis can be compared to the exposure times in order to calculate the linearity of each amplifier. These are measured by histogramming the (nearly integer) image pixels and using the histogram to compute the median and a robust (MAD-based) estimator of the standard deviation of the image pixels to sub-ADU precision.

For a series of observations of a range of exposure times, we then model the non-linear flux I' in terms of a power series of the linear flux I as:

$$I = \sum_m a_m \, I'^m \tag{16}$$

In the drift-corrected linearity sequence, I is a linear function of the exposure time t and can be expressed as st where s is a constant. Dividing out this constant from the equation yields:

$$\sum_m b_m I'^m = t \tag{17}$$

where $b_m = a_m/s$. The set of equations for the linearity ramp exposure times can then be solved for the solution vector b_m using standard linear least-squares. This model is fit using `linearity.niter` iterations of kappa sigma clipping with a rejection threshold of `linearity.clipthr` $\times\,\sigma$ and considers only those linearity ramp flats with I' between the thresholds `linearity.underexp` and `linearity.overexp`. A minimum of `linearity.mingood` good exposures are required otherwise the recipe terminates with an error.

Without loss of generality, we set $a_1 = 1$, so $s = 1/b_1$ and therefore the final set of coefficients a_m are given by:

$$a_1 = 1 \tag{18}$$

and for $m > 1$:

$$a_m = b_m/b_1 \tag{19}$$

10.1.6 Detector flat preparation and gain correction

For each of the four amplifier boundaries in the image, rectangular strips are defined on either side of the boundary for determination of the difference in background levels between the amplifiers. The strips touch at the amplifier boundary, and have dimensions of the size of the amplifier along their long axis and the parameter `gaincor.window` along their short axis. Figure 10.1 shows an example for the vertical amplifier boundary between amplifiers 1 and 2.

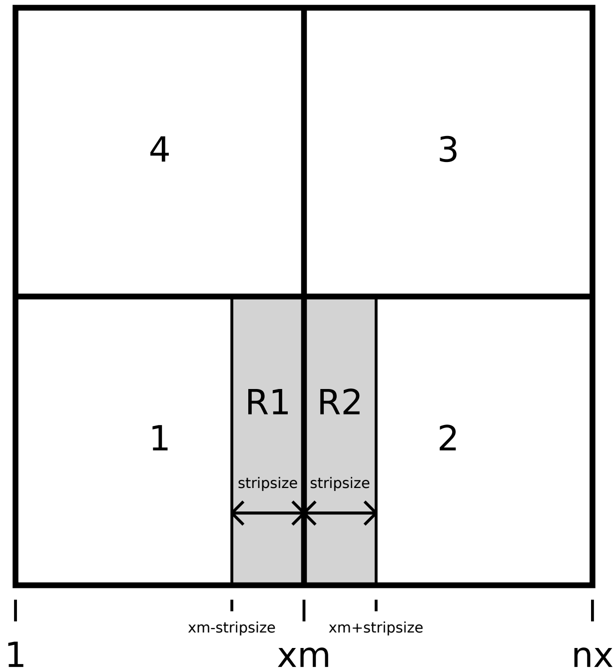

Figure 10.1: *Example of gain correction for a vertical amplifier boundary corresponding to* $x_m = \mathrm{nx}/2$ *between amplifiers 1 and 2, where the grey shaded regions R1 and R2 are the the two rectangular strips described in the text of width stripsize (=* `gaincor.window`*).*

The appropriate regions R1 and R2 are extracted from the image, one of them is flipped to reverse the direction of the short axis, and the difference image is formed by subtracting one of the rectangular regions from the other. The median of the difference image is then determined by histogramming.

By repeating this procedure for all 4 amplifier boundaries, we can write down a set of simultaneous equations of the form:

$$g_i - g_j = d_{ij}/m_{\mathrm{ref}} \tag{20}$$

where i, j are the numbers of the amplifiers, g is the relative gain, d_{ij} is the median of the difference image, and m_{ref} is the reference background level (the median of amplifier 1). These equations are solved in matrix form to obtain the relative gains g_i for amplifiers $i > 1$, where we define the relative gain of the first amplifier to be $g_1 = 1$ such that the first amplifier is used as the reference to which all of the other amplifier gains will be normalised. These relative gains are then divided out to obtain a resulting detector flat on a uniform system. This is the `UNFILTERED_DETECTOR_FLAT` product file.

The 4MOST LEDs do not illuminate the focal plane uniformly, so the resulting large scale illumination variations must be filtered out before the detector flat can be used. As a result of this filtering step, the detector flat only corrects small scale changes, e.g. pixel to pixel response changes. The sensitivity function provides the large scale corrections based on observations of astrophysical sources (standard stars) and is applied after spectral extraction.

Filtering to remove the large-scale variations from the detector flat is done using an iterative non-linear filtering technique. This is done by applying a 2D median filter with kernel size `detflat.medfil` followed by a 2D linear (boxcar) filter with kernel size `detflat.linfil` to obtain a smoothed detector flat image, and then dividing this out of the original (input) image to the filtering steps to obtain the corrected detector flat. The filters are implemented in 1D for efficiency, by applying a 1D median filter to each column of the image, and then doing the same for each row of the image. Due to the non-linear behaviour of the median, this is not exactly equivalent to a full 2D median filter with a square kernel, but it is much faster.

The gain corrections are then applied, such that dividing by the final resulting detector flat image applies the gain correction at the same time as the detector flat fielding. This is the `MASTER_DETECTOR_FLAT` product file.

10.1.7 Fibre tracing

The fibre images are defined by applying peak detection in the spatial direction to fibre flats that have been collapsed into 1D slices using block averaging along the spectral direction. The size of these blocks in unbinned spectral pixels is defined by the parameter `trace.iblock`. Tracing starts at the position specified by the parameter `trace.startline`, which is also in unbinned detector pixels, and the blocks are placed such that this line is in the centre of a block. The block containing the start line is taken as the reference block. Tracing proceeds first upwards from this starting block until it reaches the end of the detector, and then the second part of the trace is computed by returning to the starting block and tracing downwards.

The processing of each block is now described. The rectangular blocks are collapsed into 1D by taking the median along the spectral direction, to produce a 1D slice along the spatial direction. This is filtered using a 1:2:1 Hanning weighted filter kernel, and the resulting filtered array is searched for local maxima, defining a local maximum by:

$$s_{i-2} < s_{i-1} \leq s_i \tag{21}$$

and

$$s_i \geq s_{i+1} > s_{i+2} \tag{22}$$

where s_i is the output of the smoothing filter for pixel i. For a pixel index i satisfying both of these requirements, the indices of the two adjacent local minima are then located by stepping out until the value of s_j stops decreasing. The indices of the local minima jl (below i) and jh (above i) are required to satisfy:

$$s_{jl-1} > s_{jl} \tag{23}$$

and

$$s_{jl} < s_{jl+1} < \ldots < s_{i-2} < s_{i-1} < s_i \tag{24}$$

and for jh:

$$s_{jh} < s_{jh+1} \tag{25}$$

$$s_i > s_{i+1} > s_{i+2} > \ldots > s_{jh-1} > s_{jh} \tag{26}$$

If all of these constraints are satisfied, the local continuum value is estimated as:

$$c = \frac{s_{jl} + s_{jh}}{2} \tag{27}$$

and the signal to noise ratio is calculated from the unfiltered block medians themselves d_j as:

$$\mathrm{SNR} = \frac{\sum_{j=jl}^{jh} \Theta(d_j - c)}{\sqrt{\sum_{j=jl}^{jh} \Theta(d_j) + \mathrm{RON}^2}} \tag{28}$$

where

$$\Theta(x) = \begin{cases} 0, & x < 0 \\ x, & x \geq 0 \end{cases} \tag{29}$$

which is compared to the parameter `trace.detthr` to decide if the peak should be retained or discarded.

The spatial position of each peak above the detection threshold is determined using a modified intensity weighted first moment, where the terms are further weighted by:

$$w_j = \Theta(s_j - c) \tag{30}$$

such that the final position is:

$$\bar{x} = i + 1 + \frac{\sum_{j=jl}^{jh} w_j \, (j - i) \, \Theta(d_j - c)}{\sum_{j=jl}^{jh} w_j \, \Theta(d_j - c)} \tag{31}$$

If the denominator of either the SNR or the position is ≤ 0, the feature is also discarded.

Following peak detection in each trace block, the detected features are matched to the predicted trace position based on the last two blocks with an error limit of 1 spatial pixel. Accepted matches are further required to have y positions of the trace block within 2 trace blocks, i.e. there can be at most one consecutively missing trace block before the trace is abandoned. Any objects detected in $\leq 1/6$ of the trace blocks are also discarded to spurious objects detected in only one or a very small number of trace blocks. The measured x positions of each trace are fit with a trace polynomial of the form described in section 6.2.8.

Fibre traces are numbered in order of increasing x coordinate. In order to account for any missing fibres, the reference trace table is cross matched with the current trace table, using a grid search to account for any offset in spatial position. The reference trace table contains entries for all fibres, so any missing fibres can be identified. The set of identified missing fibres is checked against the information from the FIBINFO table (column FIB_ST) and any newly missing fibres are announced in the log as the recipe executes. The set of traces is adjusted by inserting blank fibres (marked as fiblive = 0 in the output) to ensure it matches the proper fibre numbering from the reference trace table, which should then also match the physical position of the fibres on the spectrograph slit, before the trace file is emitted.

Finally, the fibre mask is constructed. Pixels within $\pm\texttt{trace.width}/2$ of a trace are flagged by setting them equal to 1 using the trace polynomial. Any pixels excluded by the slit mask (true in the slit mask array) are also flagged. The resulting mask is emitted for use in the scattered light correction procedure described in the next section.

10.1.8 Scattered light correction

The fibre mask produced by the trace procedure described in the previous section is used to define the pixels of the detector that are not occupied by part of a fibre image and can be used to measure the scattered light.

A coarsely sampled background grid is then formed (with the grid specified by `scattered.nbsize`). Within each grid pixel, an iterative kappa sigma clipped median value is computed based on the histogram of the flux within the grid pixel using only those image pixels flagged by the mask as suitable for scattered light estimation. The value of “sigma” used for clipping is calculated using the median absolute deviation (MAD).

The resulting grid is then smoothed using median and boxcar filters and interpolated back onto the full input pixel grid of the image to form a scattered light map predicting the scattered light at each pixel. The resulting scattered light map is then subtracted from the 2D spectral frame.

10.1.9 PSF measurement

An empirical model of the fibre PSF is extracted from fibre flats that have been collapsed into 1D slices using block averaging with a kappa sigma clipped mean estimator in the spectral direction. The size of these blocks in unbinned spectral pixels is specified by the parameter `psf.sblock`. Within each block, an oversampled PSF is estimated by taking advantage of the trace slope and curvature within the blocks. The extent of the PSF is $\pm\texttt{psf.hwidth}$ spatial pixels, and it is subsampled by `psf.subsample` such that a total of $(2 \times \texttt{psf.hwidth} + 1) \times \texttt{psf.subsample}$ samples are produced.

Since the fibre flats have all fibres illuminated, it is necessary to correct the derived PSFs for overlap of the adjacent fibre profiles. This is done using a simple Gaussian overlap model considering the fibre of interest and its immediate neighbours, with the peak counts and FWHM values specifying the Gaussians taken from the trace table. The overlap correction is computed for a given pixel of a given fibre by determining the fraction of light in the pixel that is due to the fibre of interest, relative to the total light in the pixel from all three fibres, and correcting the measured counts accordingly.

For output, the profiles and uncertainties are computed at each physical detector spectral pixel by linear interpolation over the blocks. Parabolic interpolation is used to replace any blocks where the PSF could not be computed.

10.1.10 Spectral extraction

Two different methods are provided. For processing wavelength calibration frames and for `level=0` processing of all frames, a simple aperture sum ("boxcar" or "tramline") extraction is provided. For scientific processing, PSF-weighted spectral extraction with crosstalk correction is used.

Tramline extraction

This uses a simple aperture sum, accounting for partial pixels. The trace centre $x(y)$ is evaluated and defines the centre of the extraction aperture. The start and end points are defined as:

$$x_1 = x(y) - \frac{w}{2} \tag{32}$$

$$x_2 = x(y) + \frac{w}{2} \tag{33}$$

and corresponding summation limits of the pixels that overlap with the aperture:

$$i_1 = \mathrm{rint}(x_1) \tag{34}$$

$$i_2 = \mathrm{rint}(x_2) \tag{35}$$

where rint() is the "round to nearest integer" function in C99 and w is the parameter `extract.width`

The resulting extracted spectrum is then:

$$s(y) = (i_1 - x_1 + 0.5)\ \mathrm{image(i_1, y)} \tag{36}$$

$$+ \sum_{i_1+1}^{i_2-1} \mathrm{image}(i, y) \tag{37}$$

$$+ (x_2 - i_2 + 0.5)\ \mathrm{image}(i_2, y) \tag{38}$$

where the first and last terms are weighted to account for the fraction of the first and last pixels that overlap with the aperture, noting that the centre of the ith pixel is $x = i$. Pixels flagged as bad in the bad pixel mask are omitted. The variance image is processed according to the same equation and weights to provide the variance of the extracted spectrum.

PSF extraction

The PSF weighted extraction procedure considers an entire row of the 2D image at a time. Given an estimate of the normalised spatial profile (PSF) obtained from the procedure described in the previous section, the image row is modelled as:

$$d(x,y) = \sum_{n=1}^{N_{\text{fib}}} S_n(y)\,\psi_n(x,y) + \epsilon(x,y) \tag{39}$$

where d is a row of data along the spatial axis (x) at a given location along the spectral axis (y), $\psi_n(x,y)$ is the spatial profile of the nth fibre, S_n is a scale factor for each profile to be determined, and is actually the value for the flux of the nth spectrum at that particular wavelength. and $\epsilon(x,y)$ is a noise term with expected variance $\sigma^2(x,y)$.

This yields a system of equations of the form:

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & \dots & C_{1m} \\ C_{21} & C_{22} & C_{23} & \dots & C_{2m} \\ C_{31} & C_{32} & C_{33} & \dots & C_{3m} \\ \dots & \dots & \dots & \dots & \dots \\ C_{m1} & C_{m2} & C_{m3} & \dots & C_{mm} \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ \dots \\ S_m \end{bmatrix} = \begin{bmatrix} D_1 \\ D_2 \\ D_3 \\ \dots \\ D_m \end{bmatrix} \tag{40}$$

where

$$C_{ij}(y) = \langle \psi_i(x,y) | w(x,y) | \psi_j(x,y) \rangle_x \tag{41}$$

is the weighted overlap integral of the PSFs for fibres i and j, and

$$D_i(y) = \langle d(x,y) | w(x,y) | \psi_i(x,y) \rangle_x \tag{42}$$

is the weighted overlap integral of the ith PSF with the data in row y.

The solution to Eq. (40) is sought for each image row using Gauss-Seidel iteration. Due to the limited extent of the PSF model, the off-diagonal elements $j < i-1$ and $j > i+1$ can be approximated as zero, so in practice the matrix is tridiagonal, and it is further the case that for any realistic PSF $C_{ij}^2 \ll C_{ii}C_{jj}$ so the conditions required for stability of the Gauss-Seidel iteration are satisfied.

The maximum likelihood estimator for the extracted spectrum $\hat{S}$ is obtained when the weights w are the inverse variance, i.e. $w(x,y) = 1/\sigma^2(x,y)$. The variance in the extracted spectrum is then given by:

$$\text{var}(S_i(y)) = \frac{1}{\sum_x \frac{\psi_i(x,y)^2}{\sigma(x,y)^2}} \tag{43}$$

The 4MOST extraction is purely PSF weighted with w being simply a boolean (0 or 1) to exclude some data points from the summation. This is the limit of the maximum likelihood weight at low counts, and produces only slightly (approximately 7%) worse uncertainties at high counts. This was done to minimise the effects of crosstalk while providing a simple and natural boundary definition where the weight does not depend on the Poisson uncertainty estimated from the measured counts.

The initial boolean weights w are defined using the bad pixel mask, but are refined iteratively based on the goodness of fit to reject outliers due to cosmic ray hits, bad pixels, and the like. The residual (data – model), i.e. $d_{\text{in}} - d$

of the simultaneous profile fit is evaluated, and compared to a rejection threshold of `extract.cr_thresh` $* \sigma$. The quantity σ is the uncertainty formed as the quadrature sum of the uncertainty in the image pixels from the variance image and the profile uncertainty.

Rejected pixels are flagged in the rejection mask by the value 6 (symbolic name `DISC`, see section 6.3.7). We also allow pixels to be unflagged from the rejection mask if their residuals are less than half of the rejection threshold. These pixels are set back to `GOOD` (=0). This is done so the spectral extraction can compensate for overzealous or spurious rejection of pixels during earlier stages. This might be in the generation of the bad pixel mask, or, in the L1 pipeline, the image-level cosmic ray flagging step.

The iterative process of extracting the spectrum and discarding bad pixels is repeated `extract.niter` times. An additional recipe parameter `extract.crosstalk` is also provided to allow the crosstalk correction to be disabled for diagnostic purposes. This is done by setting all off-diagonal elements of the matrix C to zero.

10.1.11 Wavelength calibration

Wavelength calibration exposures consist of spectra of an emission line source, either a ThAr lamp, or a Fabry-Perot Etalon (FPE), where the finesse of the latter is high enough that the modes of the FPE can be treated as independent emission lines.

The extracted spectrum for each fibre is processed individually and independently. Emission features are detected in the extracted spectrum by applying the same peak detection procedure as described in section 10.1.7, with detection threshold `arc.detthr` and some minor modifications to the method as described here. The $1:2:1$ Hanning filter is replaced by a Gaussian filter with $\sigma = 1.0$ pixel. The FWHM of each feature is also determined and recorded, by locating the half-light points corresponding to:

$$d_i - c = \frac{\text{peak} - c}{2} \tag{44}$$

where "peak" is an estimate of the peak counts in the line. This is computed using parabolic interpolation about the peak pixel to reduce bias resulting from pixellation error. The positions of the half light points are computed to sub-pixel precision by interpolation within the pixel (indexed by i) containing the condition of equality written above. The difference in spectral pixel coordinate of the upper and lower half-light points gives the FWHM in pixels.

The FPE profiles are found to be asymmetric in the real instrument, with the degree of asymmetry differing between science and simultaneous calibration fibres. This causes an offset in the science wavelength calibration of approximately 2 km/s in velocity units for HRS if we use the standard estimates of the centre of gravity. As a workaround, the centre of gravity used to measure the spectral pixel coordinates of the emission features is modified by recomputing them with a restricted summation range, limited to a 5 pixel window around the initial estimate.

The pixel coordinates of the detected emission features are then transformed to wavelength. This starts with the master wavelength map (section 7.3), which gives an approximate initial guess of the wavelength for each pixel on the detector. A reference wavelength solution can also be used to refine this initial guess, where the reference file is simply a previous master wavelength solution known to be good. If a reference solution is not available for the fibre under consideration, the closest fibre is used and the wavelength map is used to adjust for the expected displacement in wavelength between the fibres.

Following assignment of these initial guesses of the wavelength to the detected features, they are then cross matched with the line list in wavelength space. The matching threshold is specified in terms of resolving power (spectral resolution) by `arc.matchwindow` which specifies the threshold in Åat 6000Åfor convenience. This is converted to resolving power internally to give it a more appropriate scaling with wavelength over the arms of the spectrograph.

For ThAr frames only, a grid search is used to account for any overall wavelength offset between the guesses and reality, for example due to shifts in the instrument. The grid is over $\pm\mathtt{arc.matchgrid}/2$ sampled at $\mathtt{arc.matchwindow}/2$ intervals in wavelength. The parameters are specified in terms of resolving power, as above. The grid search cannot be used with FPE due to the periodicity of the FPE modes, which would cause ambiguity and possible mode misidentification once the search range approaches the spacing of the FPE modes.

At this stage, if there are at least 3 points matched, a linear fit is done to remove any remaining slope error in the initial guesses, and the lines are re-matched. Finally, a wavelength solution polynomial of the form in section 6.2.13 is done and the results emitted to the wavelength solution file.

The procedure as described is used for the “simuarc” and master wavelength solutions. The OB wavelength solution correction fits a low-degree correction to the master wavelength solution, following the same procedure with the exception of the input to the polynomial fit being the wavelength residual (observed - calculated) rather than wavelength itself.

The “simufpe” procedure uses the same feature detection procedure, followed by applying the master wavelength solution to the measured pixel coordinates to obtain the wavelengths of the FPE lines. The individual detections in the (simultaneous calibration) fibres are then cross matched and all measurements of the same FPE line averaged to produce the final FPE line list.

10.1.12 Spectral resampling

The wavelength solutions are applied by resampling the spectra onto a uniform linear wavelength coordinate, defined by a start and end wavelength and spectral dispersion, which use the following fixed values:

Spectrograph	Arm	Start (Å)	End (Å)	Dispersion (Å/pix)
HRS	Red	6100.0	6788.0	0.05
	Green	5160.0	5730.0	
	Blue	3926.0	4350.0	
LRS	Red	6970.0	9500.0	0.25
	Green	5360.0	7130.0	
	Blue	3700.0	5445.0	

The dispersion values in the table were chosen to somewhat oversample the input spectral pixels to preserve resolution, and the dispersion is the same for all arms of the spectrograph allow the arms to be combined without further resampling. For binned data, the dispersion is multiplied by the spectral binning, so for example in HRS with spectral binning of 4 the dispersion would be 0.2 Å/pix.

The barycentric correction is applied at the same time as the wavelength solution, so the output wavelengths are barycentric. The mapping from output spectral pixel to wavelength is specified by a linear FITS World

Coordinate System (WCS), returned in the FITS header (see section 6.2.18).

Flux is conserved in rebinning and proceeds using drizzling if the output spectral pixels are larger than the input pixels, or if they are smaller, by linear interpolation in flux density (multiplied thereafter by the spectral dispersion to return to flux). The latter is always the case for 4MOST with the current parameters. Schematically, this proceeds proceeds by dividing the input spectrum by the wavelength interval of each pixel to obtain spectral density (in units of ADU / Å), using linear interpolation to calculate the spectral density at the central wavelength of the output pixel, treating the input spectral densities already calculated as point samples at the central wavelength of each input pixel, and finally scaling the interpolated result back to spectral counts by multiplying by the wavelength interval of the output pixel (which here is constant). The variance is propagated by applying standard Gaussian error propagation to the same procedure. If one of the input pixels being used is bad, flagged by a variance of zero, the output spectrum and variance are set to zero to flag the pixel as bad in the output.

10.1.13 Fibre flat fielding

The primary function of fibre flat fielding is to correct differences in the relative throughput of the fibres as a function of wavelength. All fibre instruments suffer from throughput differences between the fibres, but in 4MOST the tilting spine design also means that these relative throughputs can be a function of the fibre tilt used to position the fibres on target, so they are also adjusted at OB level after the fibres have been positioned.

Exposures of the laser driven light source (LDLS) in the calibration unit are used to measure the fibre flat field during the daytime (master fibre flat field) and at OB level, but the illumination of these is not expected to be completely uniform, so the reference (“true”) set of relative fibre throughputs are defined using twilight sky flat fields. The main purpose of the other LDLS-based calibrations is then to transfer these onto the fibre tilts being used for the science OBs.

The spectrum of the LDLS unfortunately contains strong spectral features, particularly in the red, which must be removed. The lamp spectrum is determined empirically by normalising the wavelength calibrated spectra in the individual fibres, and then averaging over the fibres using a kappa sigma clipped mean. The fibres are then corrected for this mean response by dividing it out. This step can be disabled by setting `ffnorm.track` to false.

The median of each response-corrected fibre from the previous step is then computed. This quantity is recorded as MED2 in the FIBINFO table.

If `ffnorm.rescale` is true, the median of the quantity MED2 is computed over all of the science fibres, and the good pixels of all spectra are rescaled by dividing by this median. This globally normalises all of the fibre flats to unity but preserves the relative throughputs of the fibres.

If `ffnorm.rescale` is false, the fibres are processed one by one. The median of the good pixels in the present fibre is calculated and the good pixels of the fibre rescaled by dividing by the median. This procedure individually normalises each fibre to unity, removing any differences in their relative throughputs.

In either case, NORMLEVEL in the FIBINFO table records the normalisation factor applied to each fibre. A final median of the good pixels is also computed for each fibre, and recorded as MED3 in the FIBINFO table.

The uncertainty in the processed fibre flat resulting from the above steps is calculated by dividing the processed fibre flat by the signal to noise ratio (SNR) of the input fibre flat. It is then squared to obtain the variance array.

If smoothing was requested by a non-zero value of `ffnorm.smooth`, this is done as the last step, where the value of the parameter is the filter kernel in (resampled) spectral pixels. 4MOST uses detector flat fielding, which should correct any pixel response non-uniformity on small scales prior to spectral extraction, so any pixel to pixel (very small scale) variations seen in the extracted fibre flats should purely be due to noise and is filtered out at this step to improve the SNR of the resulting fibre flat. This smoothing filter is a mean filter with outlier rejection based on kappa sigma clipping.

The master fibre flat is the result of this procedure applied to the daytime facility fibre flat exposures, and is divided into science spectra to apply the flat field correction. For both of the other types of fibre flat (sky and OB-level), these express corrections to the master fibre flat, so this is divided out first. Only the normalisation of the result is used, where the correction is applied by dividing this into the spectra to be corrected. Applying the sky fibre flat in this way after the master fibre flat has been applied corrects the fibre throughputs to the master set defined by the sky fibre flat, and then applying the OB-level fibre flat adjusts for the effect of fibre tilt.

10.1.14 Sky subtraction

Observations for 4MOST are designed to allocate a significant number of fibres (typically $5 - 10\%$) to sky, to be used in sky subtraction. These should be evenly distributed both spatially over the field of view, and along the slit. The former allows for monitoring of sky background gradients, and the latter to account for varying fibre LSFs as a function of location on the detector.

The first step is to combine all of the sky fibre spectra. Outlier rejection is used to remove spurious features. The mean sky spectrum is then split into continuum and sky-line components using an iterative kappa sigma clipped non-linear filter (a combination of median and boxcar). The median filter kernel is defined by `skysub.smoothing`, and the boxcar kernel is $1/3$ of the median filter kernel size. The mean sky-line spectrum resulting from this procedure is used to define a sky-line mask in an effort to isolate the emission features.

The mean sky spectrum is then subtracted from the object spectra. This can potentially be shifted and scaled, but these options are not in use for 4MOST, where the wavelength calibration should be sufficient to avoid the need to shift the sky spectrum, and the fibre normalisation resulting from the fibre flat fielding steps should ensure the fibres are accurately normalised such that there is no need to scale the sky spectrum, but this will be resisted and it may prove to be necessary to apply scaling to the sky continuum component to account for spatial variations, for example in bright time.

The result of subtracting the mean sky spectrum should be a science spectrum that is corrected for sky continuum and has the majority of the sky emission line component also subtracted. In practice, the sky emission lines vary both temporally and spatially, and there will inevitably be small residual artefacts of the sky emission lines. These are removed in the next step with PCA residual reduction.

The input to the PCA is the sky residual spectrum $\delta S(i, j)$ expressing the residual at pixel i on the wavelength axis in fibre j, where this quantity is assumed to have zero mean. The covariance of these residuals has elements:

$$C(j,k) = \sum_{i=1}^{n} \delta S(i,j)\, \delta S(i,k) \tag{45}$$

where n is the number of spectral pixels. This covariance matrix is $m \times m$ in size, where m is the number of fibres.

The covariance matrix C is decomposed into its eigenvalues λ_h and eigenvectors e_h. These are expressed in terms of fibre, but can be transformed to a more useful spectral representation using the $m \times n$ matrix δS that was input to the calculation of the covariance matrix, where the appropriate eigenvectors are then $\delta S^T e_h$.

The jth mean sky-corrected spectrum is split into continuum, $\delta S_C(j)$ and line $\delta S_L(j)$ components. These are then modelled (decomposed) into orthogonal eigenvectors in the sky line mask regions, assuming:

$$\delta S_L(j) = O(j) + N(j) \tag{46}$$

where $O(j)$ represents the filtered object spectrum (absorption and emission lines) and $N(j)$ represents the sky residuals. An estimate of the amount $a_h(j)$ of normalised sky residual eigenvector present in a give target spectrum is computed from the inner scalar products:

$$a_h(j) = e_h^T \delta S_L(j) = e_h^T O(j) + e_h^T N(J) \approx e_h^T N(J) \tag{47}$$

where we assume that on average $e_h^T O(j) \approx 0$. The $N(j)$ term can then be approximated as:

$$N(j) = \sum_{h=1}^{p} a_h(j) e_h + \epsilon(j) \tag{48}$$

with the fractional reconstruction error $\epsilon(j)$ given on average by:

$$1 - \frac{\sum_{h=1}^{p} \lambda_h}{\sum_{h=1}^{m} \lambda_h} \tag{49}$$

where the eigenvectors used in the reconstruction correspond to the p largest eigenvalues. The maximum allowable value of p is set by the parameter `skysub.neigen`, but in practice, this should be lower to limit errors due to contamination from the eigenvector-object scalar product and from noise. The actual value used is selected to produce an average reconstruction error of 2% if this can be done with less eigenvectors.

To mitigate some of the contamination issues, in practice the scalar product in Eq. (48) is computed using iterative kappa sigma clipping for outlier rejection to reduce the influence of eigenvector-object correlations and residual cosmic rays. The correction is finally applied by subtracting the reconstructed correction spectrum from the spectrum to be corrected.

10.1.15 Spectral stacking

The problem of determining the optimal weights for stacking spectra is mathematically the same as spectral extraction, discussed in section 10.1.10. Rather than spatial pixels, we have spectra, and the spatial profile is replaced by a measure of the signal in each spectrum. The maximum likelihood solution is therefore the same, the spectra should be weighted by their signal to variance ratio S/V. For stacking, the weights must be the same for all spectral pixels, to avoid introducing extra pixel to pixel noise (e.g. if the weights were per pixel, which would be very prone to noise) or spurious distortions (if there are any intrinsic differences between the spectra). Therefore we use the median signal and median variance of the spectrum to define the weight of the spectrum.

The resulting expression for the stacked spectrum is the same as the maximum likelihood estimator given in section 10.1.10 with:

$$\psi_i = \frac{\langle S_i \rangle}{\sum_j \langle S_j \rangle} \tag{50}$$

and

$$\sigma_i^2 = \langle V_i \rangle \tag{51}$$

where $\langle S_i \rangle$ is the median of spectrum i (negative values are clamped to zero) and $\langle V_i \rangle$ is the median variance of spectrum i.

A complication arises at extremely low SNR, where the noise in the estimate of the signal S becomes important. We can no longer use the S/V weighting scheme in this regime. In the extremely low SNR regime, the spectra are background limited (readout noise or sky background noise), so the optimal way to combine them is inverse variance weighting. This solves the problem because the weights no longer depend on the estimate of the signal. In this regime, we therefore substitute:

$$\psi_i = \frac{1}{N_{\text{spec}}} \tag{52}$$

The transition between these regimes is defined in terms of an estimate of the average signal to noise ratio κ of the $\langle S_i \rangle$:

$$\kappa = \frac{\sum_i \langle S_i \rangle / N_{\text{spec}}}{\sqrt{\sum_i \text{var}(\langle S_i \rangle) / N_{\text{spec}}}} \tag{53}$$

Based on consideration of the requirements on flux conservation in the stacking process, we set the threshold for use of inverse variance weighting to $\kappa \leq 50$, which corresponds to an average signal to noise ratio per pixel of approximately unity for 4MOST spectra.

Outlier rejection is implemented by detecting outliers prior to stacking and zero-weighting them during combination. To detect outliers, the continuum of each input spectrum is estimated by filtering using sequential median and linear (boxcar) filters with kernel size 501 and 255 pixels, respectively. 3 iterations of outlier rejection at 3σ (where σ is estimated using a robust median absolute deviation estimator) are used to refine the continuum estimate, which is then subtracted from the spectrum. The filtered (continuum removed) spectra are stored into a separate array and the original unfiltered spectra are also kept.

The median and 1.48*MAD = σ of the continuum removed spectra are estimated. For each output spectral pixel, the number of input spectra where the pixel is flagged as good but is above $\texttt{combine.rej}_{\texttt{t}}\texttt{hresh} \times \sigma$ in the continuum removed spectrum array is counted. If this count is ≤ 1, i.e. the pixel is only above threshold in one input spectrum, the pixel is flagged as bad to reject emission features such as cosmics that appear in only a single input file and are therefore assumed to be spurious. Emission features appearing in any larger fraction of input files or all input files are not flagged and are retained since these would correspond to real emission features.

The output stacked spectrum is finally computed as:

$$o(\lambda) = \frac{\sum_i \psi_i S_i(\lambda)/\langle V_i \rangle}{\sum_i \psi_i^2/\langle V_i \rangle} \tag{54}$$

and variance as:

$$\mathrm{var}(o(\lambda)) = \frac{\sum_i \psi_i^2 V_i(\lambda)/\langle V_i \rangle^2}{\left(\sum_i \psi_i^2/\langle V_i \rangle\right)^2} \tag{55}$$

10.2 Recipe Algorithms

This section outlines the steps taken by each pipeline recipe.

10.2.1 qmost_arc_analyse

- Debias, trim and dark correct all arc/FP images (section 10.1.1).
- Correct for detector flat field (section 10.1.1).
- Combine arc/FP images with rejection to remove cosmic ray events if more than one such image is included (section 10.1.2).
- Model scattered light and subtract it (section 10.1.8).
- Do a tramline extraction for each fibre (section 10.1.10). When processing simuarc frames, only the simucal fibres are extracted.
- Identify the emission features in each arc/FP spectrum and match the pixel positions to the arc lines in the master arc line table. The master wavelength map is used to provide an initial estimate of the wavelength versus x,y position on the detector (section 10.1.11).
- Do a robust fit to the wavelength versus pixel position data for each FP spectrum (section 10.1.11).
- If a reference wavelength solution is included, compare the new solutions with the reference.

10.2.2 qmost_bias_combine

- Trim off the pre/overscan regions to leave only the light sensitive part of the detector (section 10.1.1).
- Combine the frames with rejection (section 10.1.2).
- In conjunction with the optional bad pixel mask, calculate the desired QC statistics in both the light sensitive part of the detector as well as in the pre/overscan regions.
- If a reference bias is included in the input list, then form a difference image. Divide the difference image into the number of requested cells and do basic statistics in each cell.

10.2.3 qmost_dark_combine

- Debias and trim all dark images ((section 10.1.1).
- Normalise each image by its exposure time.
- Combine the debiased darks into a single image with rejection (section 10.1.2).
- In conjunction with the optional bad pixel mask, calculate basic statistics of the background of the combined dark frame.
- If a reference dark image has been provided, then form a difference image. Calculate basic statistics of the difference image. Divide the difference image into the number of requested cells and calculate the basic statistics in each cell.

10.2.4 qmost_detector_flat_analyse

- Debias, trim and dark correct all LED flat exposures (section 10.1.1).
- Combine into a single image with rejection (section 10.1.2).
- Determine and apply gain correction and remove illumination pattern (section 10.1.6).
- If a reference flat is included in the input list, then form ratio images of it with the new master flat. Analyse the background of the ratio image to look for systematic differences.

10.2.5 qmost_detector_noise

- Compute the sum and the difference of the detector flat frames.
- Compute the sum and the difference of the bias frames, if given, or if bias frames were not given, use the prescan regions of the detector flat frames instead.
- Compute robust average background level and noise in each of the resulting sum and difference images.
- Use these results to compute gain and readout noise for each amplifier (section 10.1.3)..

10.2.6 qmost_fibre_flat_analyse

- Debias, trim and dark correct all fibre flat images (section 10.1.1).
- Correct for detector flat field (section 10.1.1).
- For internal fibre flats, multiple exposures are stacked here at the 2D image level for better rejection of outlying pixels such as cosmic hits (section 10.1.2).
- Use fibre mask to define regions where the scattered light can be estimated. Fit the scattered light profile and subtract it off (section 10.1.8).

- Extract the fibre flat spectra from each image using trace and PSF information (section 10.1.10).
- For twilight fibre flats, check the median extracted counts for each image to reject any under or over exposed flats, and combine the extracted spectra to form a single image of combined spectra (section 10.1.15).
- If a master fibre flat was given, do OB-level fibre flat processing rather than master fibre flat processing. The master fibre flat is divided out if given.
- Work out the median flux of each combined spectrum (section 10.1.13).
- Work out the ensemble median flux of the spectra as a whole (section 10.1.13).
- Divide all the spectra by this ensemble median flux to create spectra that take the relative fibre transmission into account, if desired (section 10.1.13).

10.2.7 qmost_fpe_analyse

- Debias, trim and dark correct all FPE images (section 10.1.1).
- Correct for detector flat field (section 10.1.1).
- Combine images with rejection to remove cosmic ray events if more than one image is included (section 10.1.2).
- Model and subtract scattered light (section 10.1.8).
- Do a tramline extraction for each simucal fibre (section 10.1.10).
- Identify the emission features in each simucal fibre (section 10.1.11).
- Measure the wavelength of each feature using the provided simuarc wavelength solution (section 10.1.11).
- Match the features in each simucal fibre and combine their measurements with rejection to produce a master table of measured FPE lines and their wavelengths.
- Save the resulting table to a linelist file for use with qmost_arc_analyse.

10.2.8 qmost_linearity_analyse

- Debias, trim and dark correct all flat images (section 10.1.1).
- Remove any images that are over- or under-exposed.
- Combine remaining corrected flat images with rejection into a normalised master flat (section 10.1.2).
- Divide all the input flat images by the master to create a set of ratio images (section 10.1.4).
- Find all the pixels in each map whose value is discordant with the background by threshold values defined in the input (section 10.1.4).

- Define a pixel as bad if it is marked as discordant in at least a predetermined fraction of the images and hence create a bad pixel mask (section 10.1.4).
- Calculate median stats for linearity sequence images (section 10.1.5).
- If adjusting the stats for light source drift, then compute the medians of the frames in the monitor series and use this to work out a multiplicative correction factor for each image in the linearity sequence, which depends on the time that the observation was done. Do the correction for the light source drift (section 10.1.5).
- Combine exposure time information with the computed fluxes to create a linearity curve (section 10.1.5).
- Fit the curve.

10.2.9 qmost_psf_analyse

- Debias, trim, dark correct and detector flat correct all input images (section 10.1.1).
- Stack the fibre flats (section 10.1.2) and correct for scattered light (section 10.1.8).
- Measure the instrumental profile at each spectral coordinate along each fibre in each of the stacks (section 10.1.9).
- Record the results in a 3-dimensional map.

10.2.10 qmost_science_process

- Debias, trim and dark correct all science images (section 10.1.1).
- Do linearity correction if desired (section 10.1.1).
- Correct all science images for detector flat (section 10.1.1).
- Model and correct scattered light from each science image (section 10.1.8).
- Extract the spectra from each science image separately (section 10.1.10). QC0: tramline extraction. QC1: PSF extraction.
- Wavelength calibrate the extracted spectra by rebinning them onto a linear wavelength axis. If enough information is available in the FIBINFO table to compute the barycentric correction then this is also applied during rebinning (section 10.1.12).
- Divide the extracted spectra by the master fibre flat spectra (section 10.1.13).
- Use the provided OB and twilight fibre flats to correct the relative fibre throughputs, if given (section 10.1.13).
- Optionally correct for sky background (section 10.1.14).
- Combine the spectra from each image to form stacked spectra (section 10.1.15).
- Populate QC for individual fibre spectra in the FIBINFO table.

10.2.11 qmost_trace

- Debias, trim, dark and linearity correct the fibre flat images (section 10.1.1).
- Correct all fibre flat images for detector flat response (section 10.1.1).
- Combine all the fibre flat images with rejection (section 10.1.2).
- Using the combined flat, detect the central location of each of the fibre spectra along the dispersion direction and fit a polynomial to the spatial location versus the spectral position (section 10.1.7).
- Use the trace to define locations on the detector that are free from flux from the fibre spectra. Mark these locations on a mask (section 10.1.7).
- Compare the trace to the reference, if given. The TRACE OFFSET parameters are only produced if this reference is given to measure the offset against. For QC on OB-level fibre flats we suggest using the daytime calibration master trace file as the reference.

A Installation

This chapter gives generic instructions on how to obtain, build and install the QMOST pipeline. Even if this chapter is kept as up-to-date as much as possible, it may not be fully applicable to a particular release. This might especially happen for patch releases. One is therefore advised to read the installation instructions delivered with the QMOST pipeline distribution kit. These release-specific instructions can be found in the file `README` located in the top-level directory of the unpacked QMOST pipeline source tree. The supported platforms are listed in Section A.1. We recommend reading through Section A.2.3 before starting the installation.

A bundled version of the QMOST pipeline with all the required tools and an installer script is available from *http://www.eso.org/sci/software/pipelines/* for users who are not familiar with the installation of software packages.

A.1 Supported platforms

The QMOST pipeline is verified on GNU/Linux, but has also been successfully built on MacOS Intel platforms.

A.2 Building the QMOST pipeline

This section shows how to obtain, build and install the QMOST pipeline from the official source distribution.

A.2.1 Requirements

To compile and install the QMOST pipeline one needs:

- an appropriate version of the GNU C compiler,
- a version of the `tar` file-archiving program,
- the GNU `gzip` and `make` utilities, and
- a `perl` installation.

The pipeline itself can be run with these basic requirements (e.g. using EsoRex). To use the EDPS workflow, an EDPS installation is needed. EDPS additionally requires:

- Python 3.9 or higher

A.2.2 Downloading the QMOST pipeline

The latest release of the QMOST pipeline is available at *http://www.eso.org/sci/software/pipelines/*, as a compressed tar archive.

The distribution file is named `qmost-kit-<x.y.z>.tar.gz`, where `<x.y.z>` is a placeholder for the actual package version number.

A.2.3 Compiling and installing the QMOST pipeline

We recommend reading through this section before starting the installation. Please note that in the following examples the placeholder of the package version `<x.y.z>` needs to be replaced by the actual package version string.

1. Unpack the QMOST pipeline distribution using the following command:

   ```
   tar -zxvf qmost-kit-<x.y.z>.tar.gz
   ```

   at the shell prompt. This will create a directory `qmost-kit-<x.y.z>` containing the pipeline sub-packages.

   Note that to keep the size of the unpacked QMOST pipeline distribution to a minimum, the standard calibration data sets are distributed separately. They can be obtained from *http://www.eso.org/sci/software/pipelines/*

2. Change to the directory `qmost-kit-<x.y.z>`.

3. Execute the pipeline installer, using:

   ```
   ./install_pipeline
   ```

   The installer will then ask for the two installation directories for the software components and the calibration data respectively. If the script's defaults for the target directories are acceptable, they can be confirmed by pressing <Enter>. Otherwise an appropriate path should be given.

4. The installer will install all required pipeline components. After the installation was completed successfully a list of available pipeline recipes is shown.

A.2.4 Configuring the pipeline recipe front-end applications

For detailed information on how to set up the front–end application EsoRex, please refer to the EsoRex documentation, which is available at *http://www.eso.org/sci/software/cpl/esorex.html*

Detailed information on how to install and use EDPS is available at *http://www.eso.org/sci/software/edps.html*

B Abbreviations and acronyms

ADU	Analogue to Digital Unit
ANSI	American National Standards Institute
ASCII	American Standard Code for Information Interchange
CalibDB	Calibration Database
CPL	Common Pipeline Library
DFO	Data Flow Operations department
DFS	Data Flow System department
DO	Data Organizer
DMD	Data Management and Operations Division
DRS	Data Reduction System
ESO	European Southern Observatory
ESOREX	ESO-Recipe Execution tool
FITS	Flexible Image Transport System
FOV	Field Of View
FPE	Fabry-Perot Etalon
GUI	Graphical User Interface
LDLS	Laser Driven Light Source
LSF	Line Spread Function
MAD	Median Absolute Deviation
OB	Observation Block
PCA	Principal Component Analysis
PSF	Point Spread Function. Specifically this refers to the spatial profile.
PSO	Paranal Science Operations
QC	Quality Control
RON	Read Out Noise
SOF	Set Of Frames
UT	Unit Telescope
VLT	Very Large Telescope

C Troubleshooting Guide