Mid-infrared
E-ELT Imager and
Spectrograph

# Data Reduction Library Design

E-REP-AST-MET-1006
Issue 0-1
2020-09-07
Work package: 8.2

| | Signature and Approval | | |
|---|---|---|---|
| | Name | Date | Signature |
| Prepared | O. Czoske,<br>W. Kausch,<br>N. Sabha,<br>W. Zeilinger | | |
| Reviewed | | | |
| Approved | | | |
| Released | | | |

# REVISION HISTORY

| Issue | Date | Owner | Changes |
|---|---|---|---|
| | 2020-05-27 | Czoske | initial draft |
| 0.1 | 2020-09-27 | all | MTR release |

# TABLE OF CONTENTS

# List of Figures

# LIST OF TABLES

This page intentionally left blank

# 1 INTRODUCTION

## 1.1 Scope

This document describes the design of the data reduction software for METIS, the Mid-infrared ELT Imager and Spectrograph. It is based on the Data Reduction Library Specifications document [AD1] presented for PDR.

## 1.2 Applicable documents

[AD1] *METIS Data Reduction Library Specifications*. E-SPE-AST-MET-1001. Version 2-0. 2019-11-22.

[AD2] *Data Interface Control Document*. ESO-044156. Version 6. 2016-06-21.

[AD3] *ESO Science Data Products Standard*. GEN-SPE-ESO-33000-5335. Version 5. 2013-01-11.

[AD4] *Dataflow for ESO Observatories Deliverables Standard*. ESO-037611. Version 4. 2020-03-02. ESO.

## 1.3 Reference documents

[RD1] *METIS Operational Concept Description*. E-PLA-MPIA-MET-1057. Version 3-0. 2019-03-02.

[RD2] *METIS Coordinate system definition*. E-SPE-NOVA-MET-1090. Version 2.0. 2019-02-08.

[RD3] *METIS Data Interface Definition*. E-LIS-KUL-MET-1002. Version 1.0. 2018-12-03.

[RD4] *METIS Template Manual*. E-MAN-MPIA-MET-1058. Version 1-0. 2019-03-01.

[RD5] *METIS Calibration Plan*. E-PLA-NOVA-MET-1066. Version 3.0. 2019-11-01.

[RD6] *Detector Monitoring Recipes User Manual*. VLT-MAN-ESO-19500-4846. Version 1.2.5. 2014-01-21.

[RD7] *"METIS meets MATISSE" detector meeting*. E-MIN-CEA-MET-1005. Version 0.1. 2017-05-23.

[RD8] *VISIR Pipeline User Manual*. VLT-MAN-ESO-19500-3852. Version 1.7. 2016-09-21.

[RD9] *Atmospheric Differential Dispersion in METIS*. E-TNT-MPIA-MET-1002. Version 1-0. 2019-03-02.

## 1.4 Acronyms

This document employs several abbreviations and acronyms to refer concisely to an item, after it has been introduced. The following list is aimed to help the reader in recalling the extended meaning of each short expression:

**ADC** Atmospheric Dispersion Corrector

**ELFN** Excess Low Frequency Noise

**ELT** Extremely Large Telescope

**METIS** Mid-infrared E-ELT Imager and Spectrograph

**PWV** Precipitable Water Vapour

**QCL** Quantum Cascade Laser

**RSRF** Relative Spectral Response Function

**WCU** Warm Calibration Unit

# 2 Instrument Modes and Configurations

The following table lists the instrument modes for METIS [RD1]. All of these modes will be supported by the data reduction pipeline, where horizontal lines delimit groups of modes that can be reduced with the same set of recipes. Post-processing recipes may be available for individual modes within a group (e.g. ADI post-processing for HCI modes).

Exposures or sequences of exposures can be taken in pupil-tracking mode or in field-tracking mode. In the first case, the derotator keeps the pupil fixed with respect to the detector pixel rows and columns, while the field rotates. In the second case, the field is kept fixed, while the pupil rotates. For the pipeline, this has consequences when it comes to combining several exposures. In pupil-tracking mode, images have to be rotated in software before they can be stacked to improve signal to noise in scientific data products.

**Table 1:** The five main observing modes of METIS. The acronyms stand for: **CLC** – Classical Lyot Coronagraph; **CVC** – Classical Vortex Coronagraph; **RAVC** – Ring-apodized Vortex Coronagraph; **APP** – Apodized Phase Plate; N/A – not applicable.; **P/T** – pupil tracking; **F/T** – field tracking.

| Observing Mode | Instrument Configuration | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Subsystem** | **Band** | **IFS Setting** | **HCI Mask** | **P/T** | **F/T** | **Code** |
| **Direct Imaging** | IMG | L, M | N/A | N/A | • | • | IMG_LM |
| | IMG | N | N/A | N/A | • | • | IMG_N |
| **High Contrast Imaging** | IMG | L, M | N/A | RAVC/CVC | • | | IMG_LM_(RA/C)VC |
| | | | N/A | APP | • | | IMG_LM_APP |
| | | | N/A | CLC | • | | IMG_LM_CLC |
| | IMG | N1, N2 | N/A | CVC | • | | IMG_N_CVC |
| | | N | N/A | CLC | • | | IMG_N_CLC |
| **Longslit spectroscopy** | IMG | L, M | N/A | N/A | | • | SPEC_LM |
| | IMG | N | N/A | N/A | | • | SPEC_N_LOW |
| **IFU spectroscopy** | LMS | L, M | full IFU field | N/A | • | • | IFU_nominal |
| | LMS | L, M | extended $\Delta\lambda = 300\,\mathrm{nm}$ | N/A | • | • | IFU_extended |
| **IFU + HCI spectroscopy** | LMS | L, M | full IFU field | APP | • | | IFU_nominal_APP |
| | | | | RAVC/CVC | • | | IFU_nominal_(RA/C)VC |
| | | | | CLC | • | | IFU_nominal_CLC |
| | LMS | L, M | extended $\Delta\lambda = 300\,\mathrm{nm}$ | APP | • | | IFU_extended_APP |
| | | | | RAVC/CVC | • | | IFU_extended_(RA/C)VC |
| | | | | CLC | • | | IFU_extended_CLC |

# 3 Instrument Data Description

METIS data uses the FITS format for both raw and product data files. Raw frames are the unprocessed output of METIS instrument observations, while product frames are the result of pipeline processing.

All data files can be classified on the basis of sets of keywords stored in the FITS headers. Association of raw frames to calibration files is achieved by comparing keyword values.

**TODO: The following is taken verbatim from the PDR document, [AD1]. Updates are currently being discussed in the interface control document between ICS and PIP and will be ported here once finished. In particular the format for the N-band data from the new GeoSnap detector needs to be updated.**

## 3.1 Raw data format

All raw data files produced by METIS will be in FITS format and follow ESO standards (METIS-6081, METIS-6093), in particular as laid out in [AD2].

Data from the different subsystems (LM imager/spectrograph, NQ imager/spectrograph, LM IFU) are always stored in separate files. When more than one subsystem is recording data simultaneously, then more than one FITS file is created by one observing template.

The LM and NQ imagers are single-chip sub-instruments, hence the imaging data will appear in the primary HDU of the FITS file. The LMS integral-field spectrograph consists of four chips, hence the FITS file will consist of an empty primary data unit, whose header holds information pertaining to the exposure as a whole, and four extension units that hold the data from the four chips along with information pertaining to each chip (such as world-coordinate system).

A template may produce several exposures, each of which consists of NDIT subexposures (DITs). The exact definition of what constitutes an “exposure” or which and how many DITs will be save in a FITS file, are still under discussion. The goal will be for a file to contain the “smallest calibratable subset” of DITs, for instance one cycle of the chopping patters, or data taken in one nod position. Keeping files small in this way allows the pipeline to process data even for cases where observing blocks are only partially executed.

Where applicable, all the DITs belonging to an exposure may be saved in a 3D-cube format. This is described in more detail for the various observing modes in the following sections.

The raw data should include World Coordinate Systems based on the telescope pointing, derotator angle and the design characteristics of the telescope and instrument. Instrument-internal coordinates (e.g. angles of movable components inside METIS) will follow the definition in [RD2] (METIS-6070).

The list of these FITS header keywords used by METIS is kept in [RD3].

## 3.2 LM-band Imager and Spectrograph

The LM-band imager is equipped with a 2k $\times$ 2k HAWAII2RG detector with a pixel scale of 5.47 mas. A number of rows and columns along the edges of the detector will be masked (see Sect. 8.2 of [AD1]).

Grisms in the imager pupil wheel in conjunction with a number of slit masks in the CFO focal plane provide low-resolution spectroscopy covering the entire L and M bands, respectively, with $R \gtrsim 1400$.

The basic templates for LM-band imaging are ([RD1], [RD4]):

- `METIS_img_lm_obs_AutoJitter`
- `METIS_img_lm_obs_GenericOffset`
- `METIS_img_lm_obs_FixedSkyOffset`

Each of these templates moves the target position between exposures, either using the internal (CFO-PP2) chopper or telescope offsets, and takes an exposure at each position, consisting of subintegrations defined by DIT and NDIT. Depending on the setting of a Boolean template parameter (`DET CUBE MODE`), all DITs are stored as layers of 3D cube, or a co-added frame is stored as a 2D image. The 3D cube or 2D image are written out in the primary HDU of the FITS file.

The header of the FITS file will contain all information that pertains to the exposure. This should include information about the position of the internal chopper (`SEQ.CFO.CHOP.POSANG`, `SEQ.CFO.CHOP.THROW`), the telescope offsets (`SEQ OFFSET1`, `SEQ OFFSET2`) and the characterisation of the observation as `OBJECT` or `SKY` (in `DPR.TYPE`).

Similar considerations apply to the spectroscopic and coronagraphic templates, where pointing offsets are however restricted by the slit or coronagraphic masks.

## 3.3 N-band Imager and Spectrograph

The N-band imager is equipped with a 2k $\times$ 2k GeoSnap detector with a pixel scale of 6.8 mas. A number of rows and columns along the edges of the detector will be masked.

A grism in the imager pupil wheel in conjunction with a number of slit masks in the CFO focal plane provide low-resolution spectroscopy in the N band with $R \gtrsim 400$.

Subtraction of the thermal background in the N band will be done using chopping at a few Hertz using the internal chopper and regular nodding using telescope offsets. The basic templates for N imaging are

- `METIS_img_n_obs_AutoChopNod`
- `METIS_img_n_obs_GenericChopNod`

At each nod position, a series of exposures are taken at alternating chop positions. Depending on the setting of the template parameter `DET CUBE MODE`, all exposures are stored as layers of a 3D cube or they are precombined in a 2D image. Another chop cycle is then taken at another nod position, and so on. Whether separate nod positions are stored as individual FITS files or as extension units of a single FITS file remains to be determined. As explained in Sect. 3.1, there is a preference for small FITS files containing minimal calibratable subsets of DITs.

The primary header of the FITS file will contain all information that pertains to the chop cycle or the sequence of chop/nod cycle. The headers of the individual files or extensions will allow unique determination of the chop/nod positions.

## 3.4 LM-band Integral Field Unit

METIS will contain an image slicing integral-field unit (IFU) for high-resolution spectroscopy in L- and M-band ($R \approx 100,000$). This will be referred to as "LMS" (LM spectrograph).

The LMS is equipped with a $2 \times 2$ mosaic of HAWAII2RG detectors separated by small gaps. A number of rows and columns along the edges of the detector will be masked (see Sect. 8.2 of [AD1]).

In the nominal mode, the field will be resolved into 28 spatial slices covering a field of view of $1.00 \times 0.58\,\mathrm{arcsec}^2$. The slit width (i.e. the across-slice pixel scale) is 20.7 mas; the along-slice pixel scale is 8.2 mas. Spectrally, the slices span a short wavelength range of width 37 nm and 70 nm, depending on the central wavelength setting, which is selected by rotation of the echelle grating.

The extended mode provides a larger wavelength range coverage at the expense of a reduced field of view. The dispersed two-dimensional image from the pre-disperser is spectrally sliced, resulting in six non-overlapping wavelength subranges (selected by the echelle angle) onto the detector, each with three spatial slices.

The layout of spectra on the detector array in the nominal and extended modes is shown in the left and right panels of Fig. 1, respectively.

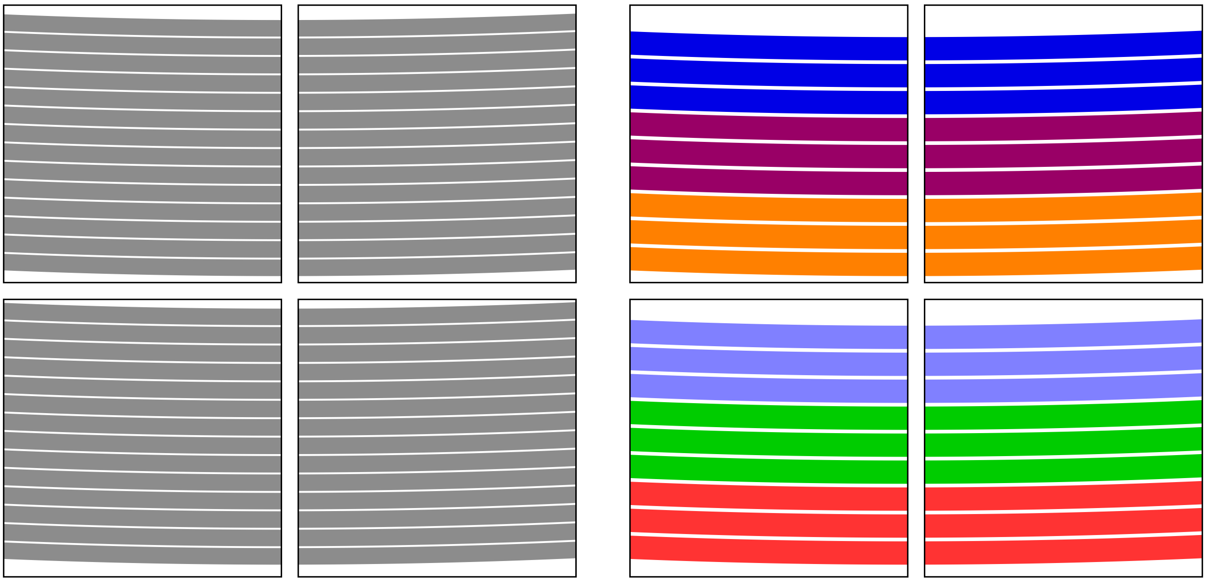


**Figure 1:** Layout of the LMS/IFU detector mosaic in the nominal (left) and extended (right) modes. The dispersion direction is horizontal. In the nominal mode, all 28 slices cover the same wavelength range. In the extended mode, slices marked by the same colour cover the same wavelength ranges, while the wavelength ranges of the six groups of slices each are not contiguous. The position and curvature of the slices are indicative only.

The basic templates for LM integral-field spectroscopy are:

- `METIS_ifu_obs_FixedSkyOffset`
- `METIS_ifu_obs_GenericOffset`

Both templates move the target position between exposures, using the internal chopper or the telescope. At a given position a number of exposures with DIT/NDIT are taken. Depending on the setting of the template parameter `DET CUBE MODE` all the DITs may be stored as layers of a 3D cube (burst mode) or co-added into a 2D image.

As the LMS contains an array of four detectors, there will be four image or cube extensions in the FITS file for one exposure.

The primary header of the FITS file will contain all information that pertains to the exposure. This will include information on the position of the internal chopper, the telescope offsets, and the type of observation (`DPR.TYPE=OBJECT` or `SKY`).

A typical sequence of LMS exposures will go through a series of dispersion grating settings in order to fill gaps in the instantaneous wavelength coverage ("spectral dithering"). Finally, the field will be rotated by 90 degrees and the observing sequence repeated to permit full image reconstruction (cf. Sect. 8.9 of [AD1]). The FITS header information will ensure that the position of each exposure within this complex sequence can be uniquely identified.

## 3.5 File classification keywords

**TODO: This section will contain the list of files with the values of kewords `DPR.CATG`, `DPR.TYPE`, `DPR.TECH`, `DO Category` in accordance with [AD2].**

## 3.6 Reduced data format

All reduced data will be provided in FITS format compliant with [AD3].

# 4 Data Processing Overview

The METIS data reduction system runs in different environments and serves various purposes. According to the setting, the following pipeline levels are distinguished [AD4]:

**Quality Control Level 0 (QC0):** The QC0 pipeline runs automatically in real time on a dedicated pipeline workstation in the instrument control room at the observatory. Its purpose is to analyse every FITS file created by the instrument and produce quality control parameters that allow assessment of whether the observation and instrument performance were within specifications. The appropriate reduction recipe is triggered either when a single FITS file is delivered to the workstation or when a template is finished. The files are classified based on header keywords, grouped and associated to the necessary standard calibration files.

**Quality Control Level 1 (QC1):** The goal of the QC1 pipeline is to produce certified calibration products from calibration observations as well as to produce QC parameters that are used to check the quality of observations and to monitor observing conditions and instrument health. Calibration products and QC parameters are ingested into the ESO Science Archive.

**Quality Control Level 2 (QC2):** The QC2 pipeline produces Science Data Products compliant with [AD3] as well as QC parameters derived from science exposures. It runs offline in an automatic way and uses the best calibration products for the night of observation (produced by the QC1 pipeline). Science data products and QC parameters are ingested into the ESO Science Archive.

**Science-Grade Desktop Environment:** The pipeline recipes are delivered to the astronomical community to enable users to reduce data in an optimal and interactive way. Recipes can be run from the command line using the `esorex` front-end or in the context of a `Reflex` workflow. While the desktop recipes are identical to those used in the QC2 pipeline, the user can change recipe parameters to optimise the reduction. Within the `Reflex` environment, interactive tools are provided that allow the user to assess the quality of individual reduction steps and to repeat them with different parameters. The products of this pipeline are compliant with [AD3].

The following sections describe the recipes used in the QC1, QC2 and desktop pipelines. Recipes used in the QC0 environment may need to be streamlined to allow them to run in real time.

## 4.1 Required calibrations

Table 2 (taken from [RD5]) lists the main calibration steps that are required for each instrument mode.

**TODO: Do we apply NCPA + PSF to HCI data? For ADI a simple recipe is foreseen.**

**Table 2:** Overview of required calibrations per instrument mode. The IFU modes refer to both the nominal configuration and to the extended wavelength configuration. From [RD5].

| | Dark | Flat | Wave | Background subtraction | Telluric | Flux | Distortion | NCPA + PSF | RSRF |
|---|---|---|---|---|---|---|---|---|---|
| IMG_LM | ✓ | ✓ | — | Dither | — | ✓ | ✓ | — | — |
| IMG_LM_(RA/C)VC | ✓ | ✓ | — | ADI | — | ✓ | ✓ | ✓ | — |
| IMG_LM_CLC | ✓ | ✓ | — | ADI | — | ✓ | ✓ | ✓ | — |
| IMG_LM_APP | ✓ | ✓ | — | Dither + ADI | — | ✓ | ✓ | ✓ | — |
| SPEC_LM | ✓ | — | ✓ | Dither along slit | ✓ | ✓ | ✓ | — | ✓ |
| IFU | ✓ | — | ✓ | Dither | ✓ | ✓ | ✓ | — | ✓ |
| IFU_APP | ✓ | — | ✓ | Dither + ADI | ✓ | ✓ | ✓ | ✓ | ✓ |
| IFU_(RA/C)VC | ✓ | — | ✓ | ADI | ✓ | ✓ | ✓ | ✓ | ✓ |
| IFU_CLD | ✓ | — | ✓ | Dither + ADI | ✓ | ✓ | ✓ | ✓ | ✓ |
| IMG_N | — | ✓ | — | chop/nod | — | ✓ | ✓ | — | — |
| IMG_N_CVC | — | ✓ | — | three-point chopping | — | ✓ | — | ✓ | — |
| IMG_N_CLC | — | ✓ | — | out-of-field chopping | — | ✓ | — | ✓ | — |
| SPEC_N_LOW | — | — | ✓ | chop/nod along slit | ✓ | ✓ | ✓ | — | ✓ |

## 4.2 Imaging in LM and N

**Note: The pipeline layout has been modified compared to the PDR design in order to achieve better modularity. Basic reduction and background subtraction have been split into two recipes that now are applied to both standard and science data. Integration of HCI into this workflow requires more work: HCI images will be treated the same way at least through basic reduction, possibly through background subtraction. ADI combination may require a separate recipe, at least for some HCI configurations.**

The purpose of the pipeline is to correct or remove contributions from the instrument, telescope, and atmosphere and produce science-grade data products. In the case of the METIS imaging modes the main contributions to correct or remove are dark current, flatfield, bad pixels, and, most importantly, thermal background emission from the sky and the telescope. Further effects include persistence, cross-talk, geometric distortions, etc. The final product of the imaging pipeline is one or more flux-calibrated image(s) in units of photons/s/pixel. Several images can be stacked into a single possibly mosaiced image.

Due to the differences in characteristics between the HAWAII2RG detector used for imaging in the L and M bands and the GeoSnap detector used for the N band, the operational concept for the two imager subsystems are quite different. This induces differences in the way the data have to be reduced.

The GeoSnap detector has more stable gain than AQUARIUS detector, which was still in the baseline at PDR. Chopping is still necessary, albeit at a lower frequency of a few Hz, and the standard chop/nod technique will be employed for background subtraction. As the dark signal is automatically removed when the exposures from the different chop and nod positions are combined no master dark is required for the reduction of science data. Flat fielding may be possible, pending further investigation of the detector stability

Observations and reduction of LM band data with the HAWAII2RG detector can proceed as in the near infrared. After dark subtraction and flat-fielding, the background is estimated from a series of dithered science exposures or from exposures on a nearby blank patch of sky.

The association maps for the current designs of the imaging pipelines in LM and N are shown in Figs. 2 and 3, respectively.

**TODO: For HCI data, ADI may need to be part of reduction recipe if individual background subtracted images are the goal?**

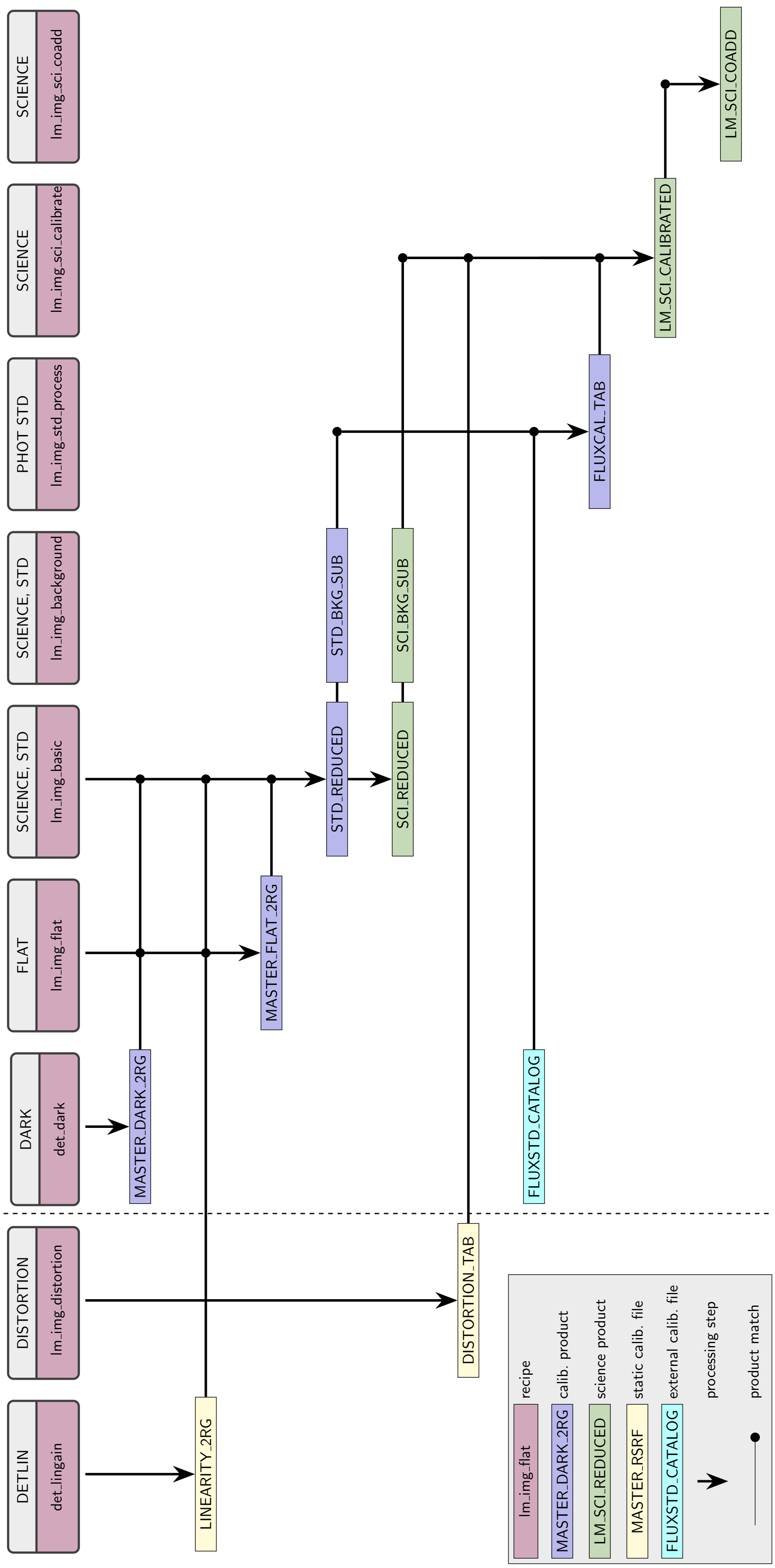



**Figure 2:** Association map for imaging in the LM band. The figure shows only the primary product created from each recipe; for a full list of products refer to the recipe descriptions in Sect. 5.2. The dashed line separates calibration tasks that are done at AIT or infrequently during operations from daily tasks. The prefix "`metis_`" has been omitted from the recipe names to improve clarity. The product names omit "`LM_`".

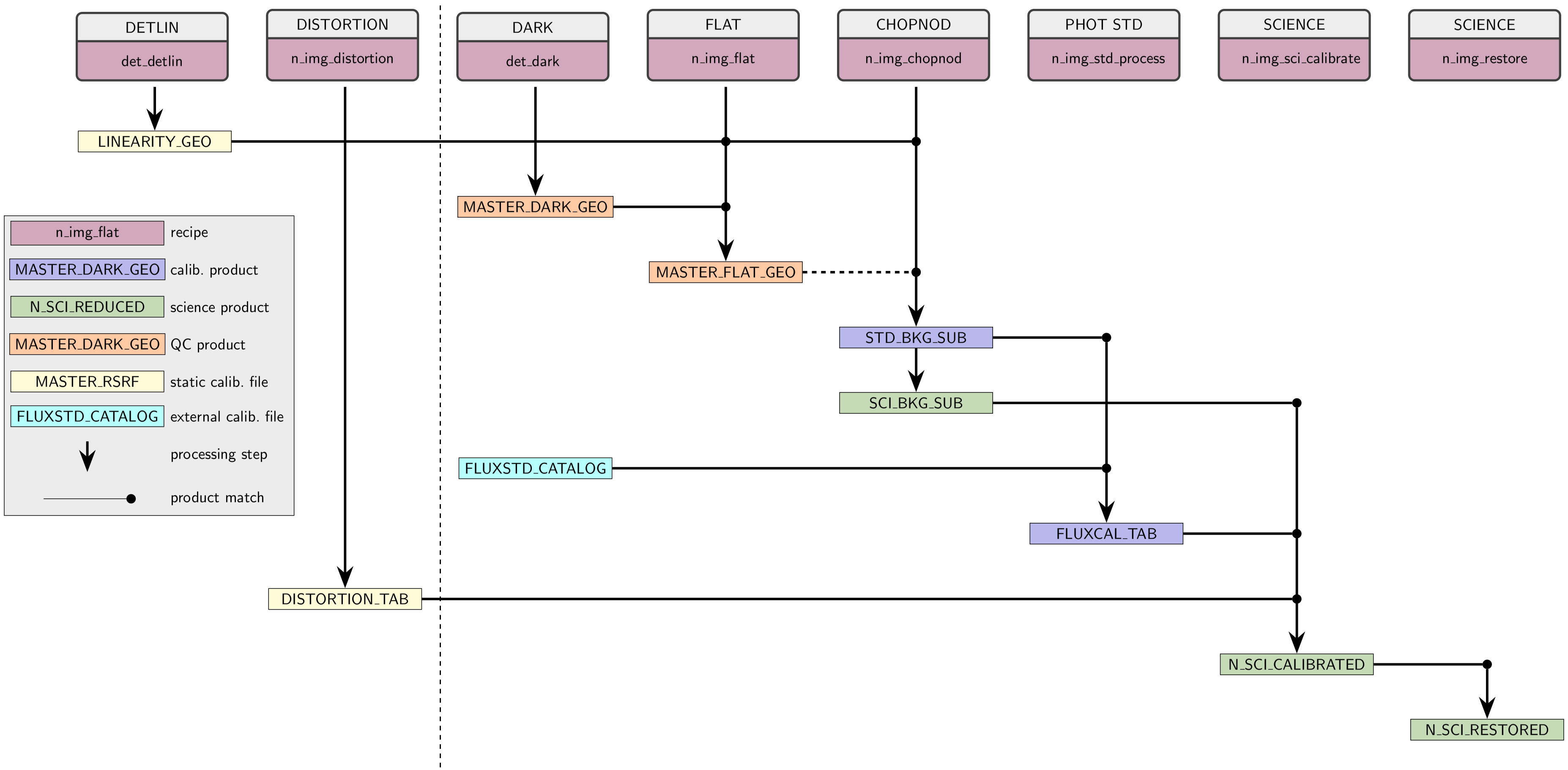



**Figure 3:** Association map for imaging in the N band. The figure shows only the primary product created from each recipe; for a full list of products refer to the recipe descriptions in Sect. 5.3. The dashed line separates calibration tasks that are done at AIT or infrequently during operations from daily tasks. The prefix "`metis_`" has been omitted from the recipe names to improve clarity. The product names omit "`N_`".

## 4.3 Long-Slit Spectroscopy in L/M- and N-bands

The purpose of the pipeline is to correct or remove contributions from the instrument, telescope, and atmosphere and produce science-grade data products for the L/M- and N-band long-slit spectroscopy mode. Since the detector properties are not fully specified, especially of the new Geosnap, we currently assume the same reduction cascade for both spectral ranges LM and N, respectively. However, to keep flexibility and independence of both branches, we define different recipes for the time being, although they will be mostly based on the same algorithms. We therefore focus here on the LM-band only.

Figure 4 shows the reduction cascade and the association map for the recipes handling L/M-long-slit spectroscopy data. Table 3 contains the data processing table for this mode. For the time being it is not clear whether a geometric distortion correction will be needed. We therefore consider to investigate the geometry of atmospheric lines for this purpose. These lines also will serve as reference frame for the wavelength calibration.

**Table 3:** Data Processing table for LM/N long-slit spectroscopy calibration modes

| Data Type (Templates) | Classification Keywords | Recipe (Level) Processing steps | FITS Keywords | CalibDB | Products |
|---|---|---|---|---|---|
| DARK | DPR.CATG==CALIB<br>DPR.TYPE==DARK<br>DPR.TECH==IMAGE | metis_det_dark | Exposure time | | Averaged dark frame<br>Bad pixel map |
| FLAT | DPR.CATG==CALIB<br>DPR.TYPE==FLAT<br>DPR.TECH==SPECTRUM | metis_LM_lss_rsrf | Exposure time | dark | Averaged, normalized flatfield<br>Bad pixel map |
| SCIENCE | DPR.CATG==SCIENCE<br>DPR.TYPE==LSS<br>DPR.TECH==SPECTRUM<br>PRO.CATG==SPECTRUM | metis_LM_lss_wave | Object name<br>Exposure time | ATM_LINE_CAT | wavelength solution |
| FLUX,STD | DPR.CATG==FLUX,STD<br>DPR.TYPE==LSS<br>DPR.TECH==SPECTRUM<br>PRO.CATG==SPECTRUM | metis_LM_lss_flux | Object name (Flux STD)<br>Exposure time | reference flux of STD<br>ATM_LINE_CAT | Science grade, flux calibrated spectrum |
| SCIENCE | DPR.CATG==SCIENCE<br>DPR.TYPE==LSS<br>DPR.TECH==SPECTRUM<br>PRO.CATG==SPECTRUM | metis_LM_lss_sci | Object name<br>Exposure time | | Science grade spectrum |
| SCIENCE | DPR.CATG==SCIENCE<br>DPR.TYPE==LSS<br>DPR.TECH==SPECTRUM<br>PRO.CATG==SPECTRUM | metis_LM_lss_tac | Object name<br>Transmission curve | | Science grade telluric<br>Absorption corrected spectrum |

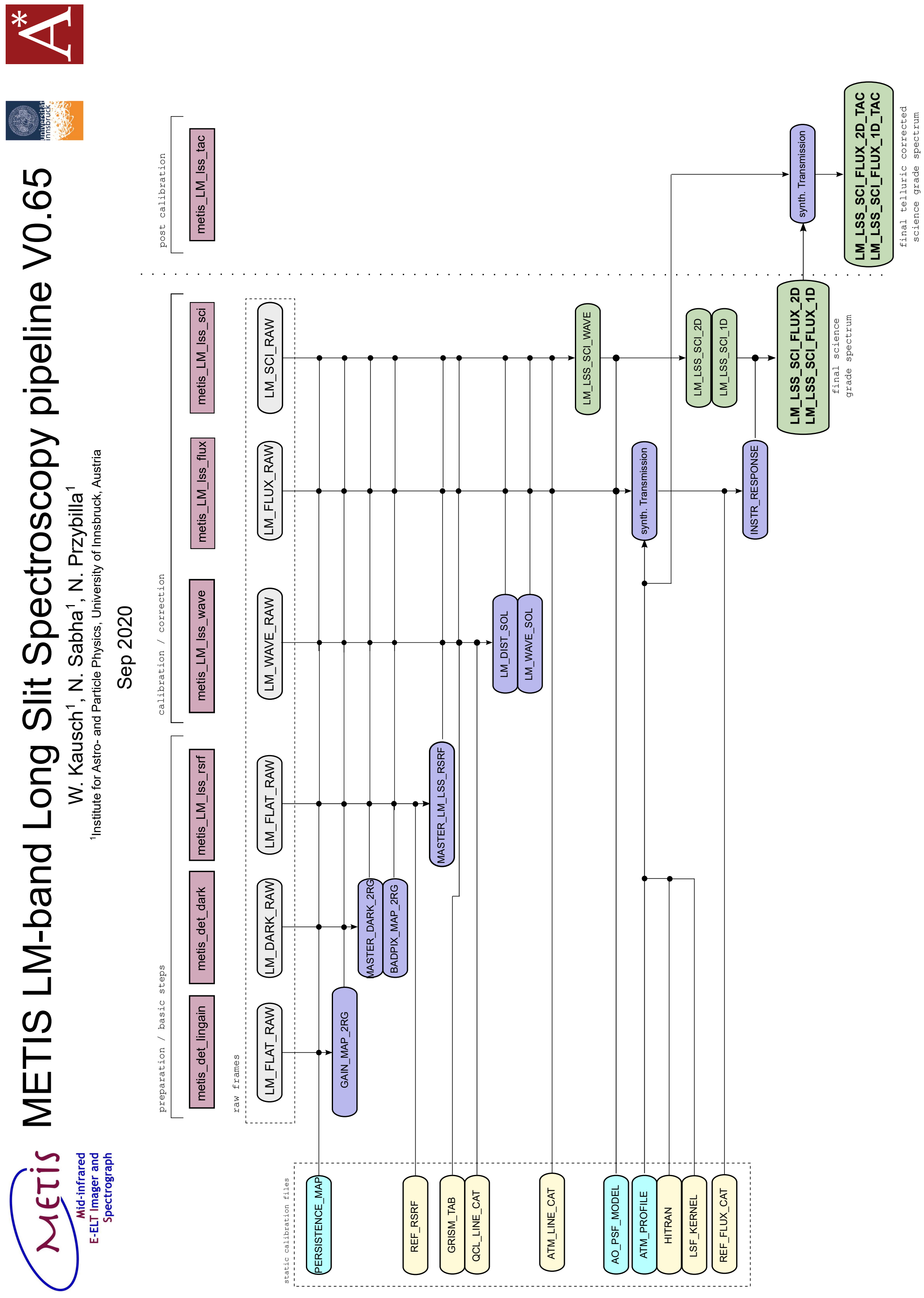



**Figure 4:** Reduction cascade and association map for long-slit spectroscopy in the LM bands.

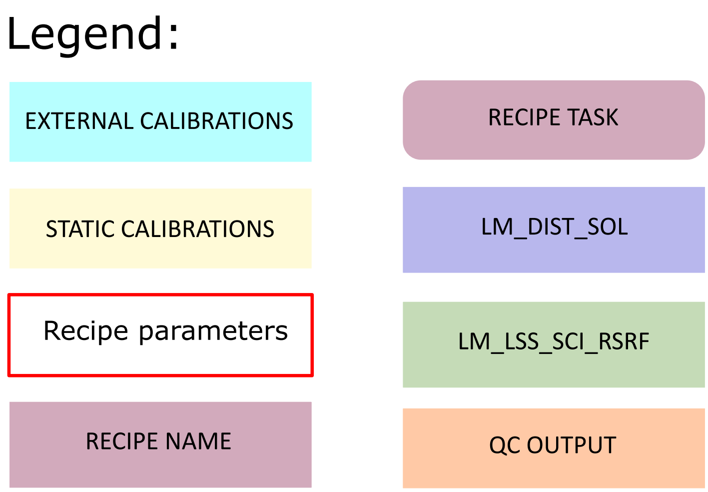



**Figure 5:** Legend of the coloured boxes in the workflows.

## 4.4 LMS: integral-field spectroscopy

The LMS pipeline has not yet been revised since PDR, hence the description in [AD1] applies. For reference, the association map is shown in Fig. 6.

We will consider rearranging the recipes to be in line with the imaging pipelines. This would entail handling basic reduction and background subtraction for of both science and standard exposures in common recipes (`metis_lms_basic`, `metis_lms_background`), then having a recipe to analyse the standard observations (`metis_lms_photstd`). The science exposures are then fully calibrated (`metis_lms_calibrate`). A full set of exposures would then be assembled and restored with a fully sampled PSF in a post-processing recipe (`metis_lms_combine`).

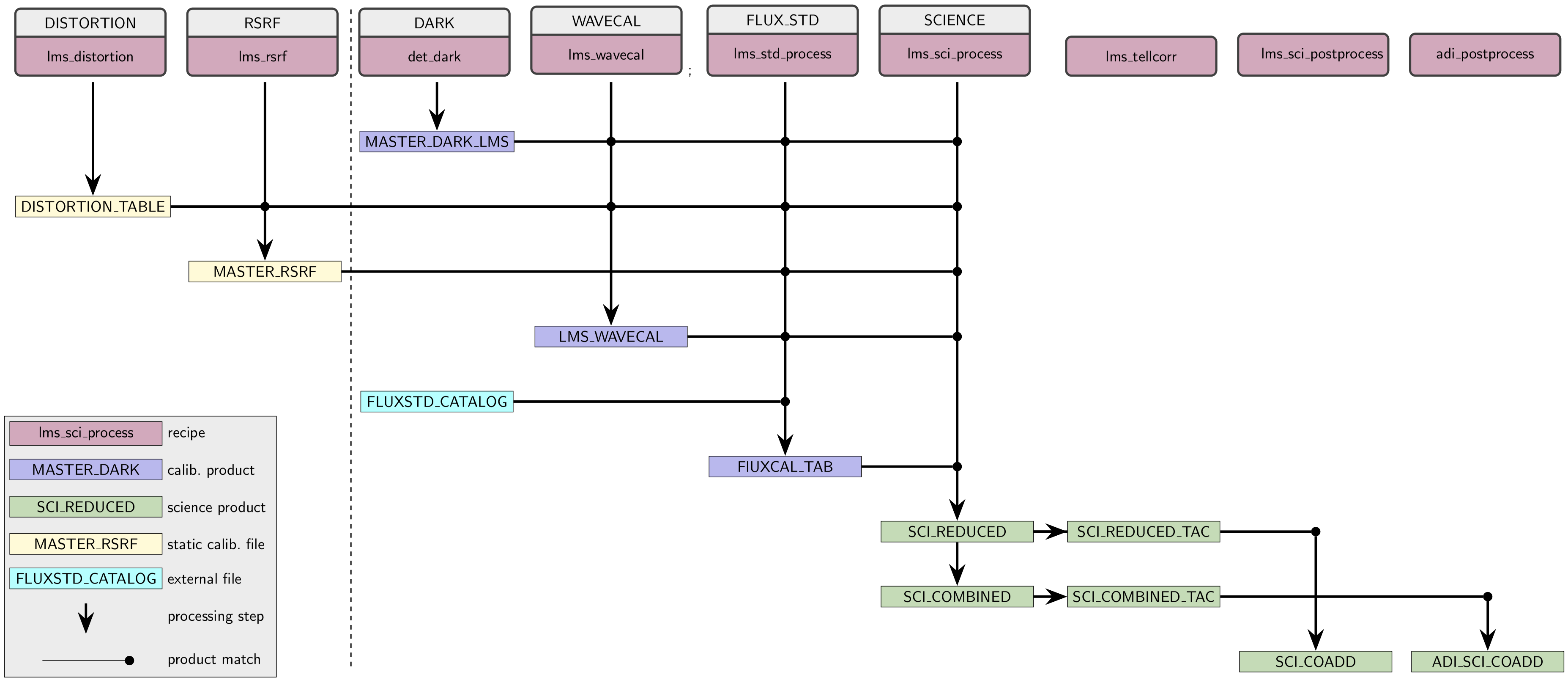
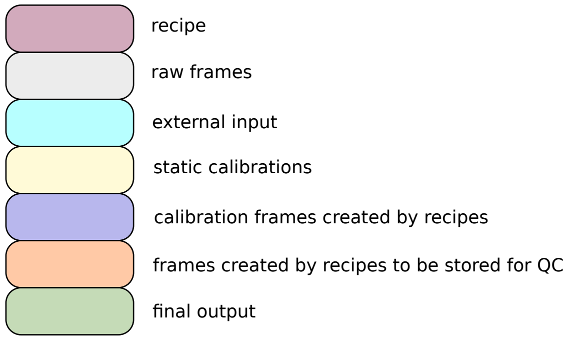



**Figure 6:** Association map for IFU spectroscopy in L- and M-band (LMS). The figure shows only the primary products created by each recipe; for a full list of products refer to the recipe descriptions in Sect. 5.5. The dashed lines separates calibration tasks that are done at AIT or infrequently during operations from daily tasks. The prefix "metis_" has been omitted from the recipe names to improve clarity.

# 5 Pipeline Recipes

Throughout this document we use the following color scheme for the recipe workflows:




## 5.1 Detector calibration recipes

METIS will have three focal plane detector arrays:

- One 2k $\times$ 2k HAWAII2RG detector used for LM-band imaging and slit spectroscopy.
- One 2k $\times$ 2k GeoSnap (Teledyne) detector used for N-band imaging and slit spectroscopy.
- An array of four 2k $\times$ 2k HAWAII2RG detectors used for LM-band integral-field spectroscopy.

This section lists recipes that calibrate detector characteristics independent of a specific instrument mode. Where `_det` appears in FITS keywords of input or product files, it is taken to mean `_2RG`, `_GEO` or `_LMS` according to the detector array for which data are being processed.

### 5.1.1 Detector linearity and gain determination

The recipe determines detector (non-)linearity and absolute detector gain from a set of flat-field frames taken with the broad-band lamp over a range of detector exposure times (DITs) and flux levels. The recipe structure will be similar as for `detmon_ir_lg` [RD6]; however, further insight into detector behaviour (in particular of GeoSnap) may necessitate development of more complex procedures.

The linearity curve is given by the measured background level as a function of exposure time for constant illumination. For each pixel the coefficients of a polynomial fit (order TBD) will be recorded in a coefficient cube, which can in turn be used to correct for non-linearity in other recipes. Pixels whose coefficients differ significantly from the majority of pixels will be marked as bad.

Detector gain is typically computed pixelwise as the slope of a linear fit of the variance against the mean (or median) values over a set of frames taken over a range of DITs and illumination levels. For mid-infrared detectors that suffer from Excess Low Frequency Noise (ELFN), e.g. the AQUARIUS detector, this approach does not work. The GeoSnap is not expected to show ELFN, hence gain determination is probably possible.

The set of calibration frames used for this recipes will include exposures with WCU window closed (`LAMP OFF`), which will be used as 'dark' frames that captur thermal emission within the instrument. This is subtracted from all other exposures in the sequence.

| | |
|---|---|
| Recipe name: | metis_det_lingain |
| Purpose: | determine non-linearity and gain of the detectors |
| Requirements: | METIS-5997 |
| Type: | Calibration |
| Templates: | METIS_img_lm_cal_DetLin<br>METIS_img_nq_cal_DetLin<br>METIS_ifu_cal_DetLin |
| Input data: | set of FLAT,LAMP frames taken with increasing DIT/illumination<br>instrument dark (FLAT,OFF) |
| Matched keywords: | Detector ID |
| Algorithm: | Subtract instrument dark<br>Compute mean and variance for each frame.<br>Gain is determined as the slope of variance against mean.<br>Fit polynomial of value as a function of DIT and illumination level for each pixel.<br>Flag pixels with coefficients significantly different from the mean of all pixels. |
| Output data: | GAIN_MAP_det<br>LINEARITY_det<br>BADPIX_MAP_det |
| Expected accuracies: | TBD |
| QC1 parameters: | QC LIN GAIN MEAN<br>QC LIN GAIN RMS<br>QC LIN NUM BADPIX |
| hdrl functions | hdrl_imagelist_sub_image<br>hdrl_bpm_fit_compute |

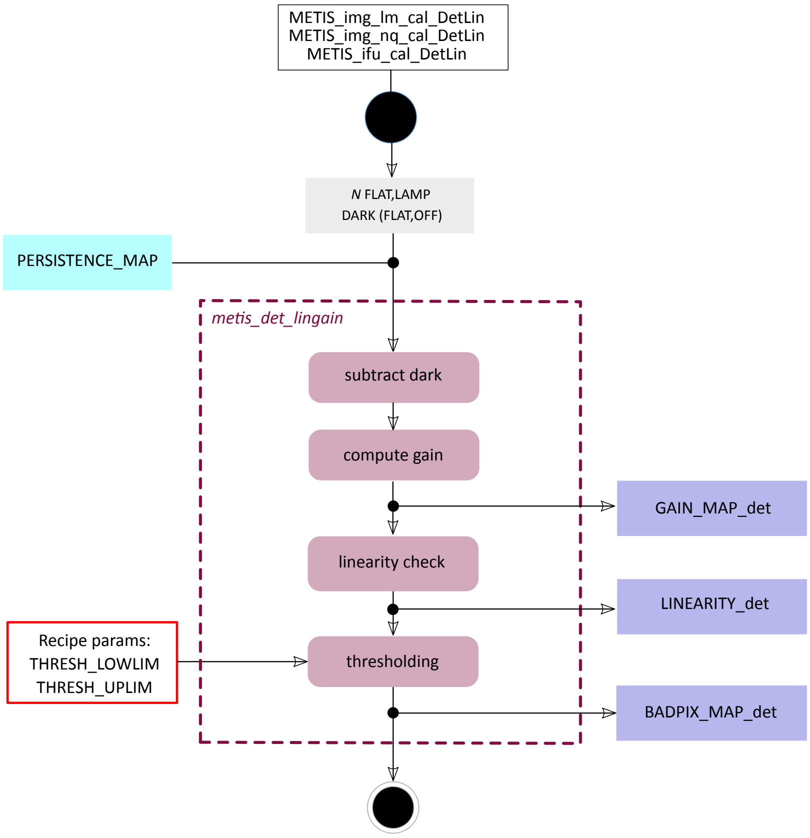



**Figure 7:** `metis_det_lingain` – determination of linearity and gain of the detectors.

### 5.1.2 Master dark

Darks are taken in daytime for all science detectors [RD5]. The data will be classified by detector (e.g. DET.ID and DET.CHIP.ID) and exposure time (DET.DIT and DET.NDIT). There will be "METIS-dark" (with the CLOSED position of the CFO-PP1 wheel) and "Imager-dark" (with the CLOSED position in the subsystem PP1), to be distinguished by keyword **TBD**. The former will be used for pipeline processing, the latter for monitoring purposes.

Each set of raw dark frames is processed into a master dark. The recipe also produces bad pixel mask by identifying cold, hot or deviant (i.e. hot or cold) pixels whose dark current differs significantly (by more than $\pm 5\sigma$) from the average over the detector.

| | |
|---|---|
| Name: | metis_det_dark |
| Purpose: | determine the dark current of the detectors |
| Requirement: | METIS-6063 |
| Type: | Calibration |
| Templates: | METIS_all_cal_dark |
| Input data: | A set of DARK frames from the same detector with the same integration time. |
| Parameters: | Combination method (median, mean, sigclip,...) |
| | Parameters for combination methods |
| | Threshold for bad-pixel identification |
| Algorithm: | Compute median or average of input frames to improve statistics. |
| | Flag deviant pixels in master dark. |
| Output data: | MASTER_DARK_det |
| | BPM_COLD_det |
| | BPM_HOT_det |
| | BADPIX_MAP_det |
| Expected accuracies: | **TBD** |
| QC1 parameters: | QC DARK MEAN |
| | QC DARK MEDIAN |
| | QC DARK RMS |
| | QC DARK NBADPIX |
| | QC DARK NCOLDPIX |
| | QC DARK NHOTPIX |
| | (more **TBD**) |
| hdrl functions | hdrl_bpm_3d_compute |
| | hdrl_imagelist_collapse |

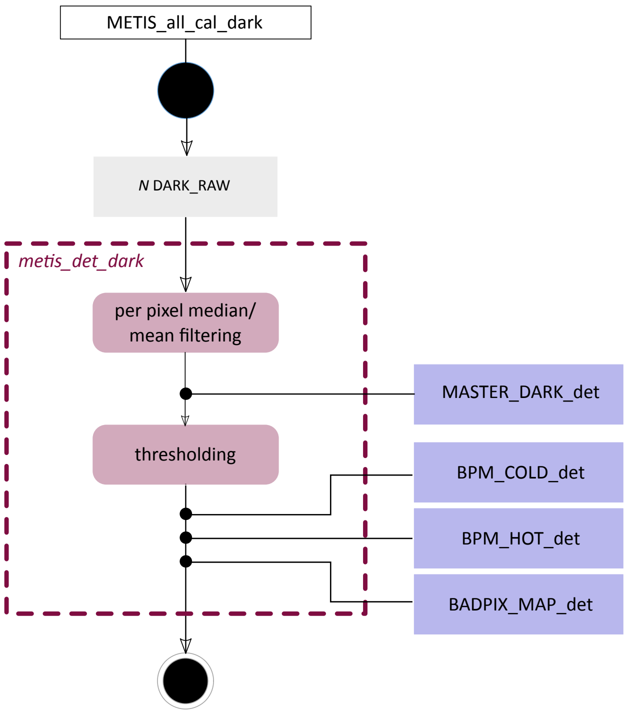



**Figure 8:** `metis_det_dark` – creation of master dark and bad pixel maps

## 5.2 LM-band imaging

### 5.2.1 LM-band imaging flatfield

The purpose of the flat-field calibration is to determine pixel-to-pixel gain variations and large scale illumination variations (due to inhomogeneities of optical elements in the telescope or instrument). Calibration frames are obtained either during day time using the black-body lamp of the Warm Calibration Unit (WCU) (internal flats) or by taken images of the twilight sky (twilight flats). Advantages and disadvantages of the two types of flat are discussed in [RD5]. Since the operational concept for twilight flats needs to be refined during commissioning at the telescope, the current recipe design is primarily valid for internal flats.

This recipe creates a master flat for the HAWAII2RG detector (LM-band imaging) from lamp or sky images matched by various setup parameters as detailed below. A set of internal flats includes a number of exposures with `LAMP OFF`, which will be used for dark subtraction. For twilight flats a master dark will be subtracted. The master flat is obtained by the slope of a linear fit of the pixel values against the illumination level of the exposures.

The quality control parameters give various statistics for each input frame (mean, standard deviation, etc.), the standard deviation of the normalised master flat and the number of bad pixels identified by the recipe. If a bad-pixel map is provided on input, it is updated, otherwise a new one is created.

| | |
|---|---|
| Name: | `metis_lm_img_flat` |
| Purpose: | Create master flat field for the LM-band imaging detector. |
| Requirements: | METIS-6096 |
| Type: | Calibration |
| Templates: | `METIS_img_lm_cal_LampFlat` |
| | `METIS_all_cal_TwilightFlat` |
| Input data: | Flat field images taken with lamp or sky. |
| | Master dark (for twilight flats) |
| | Bad pixel map |
| Matched keywords: | Detector ID |
| | Filter ID |
| | ADC ID |
| | Flat type (internal or twilight) |
| | possibly others (e.g. coronagraphic mask, **TBD**) |
| Recipe parameters: | Combination method (`mean`, `median`, `sigclip`, ...) |
| | Parameters for combination methods |
| | Threshold for bad-pixel identification |
| Algorithm: | For internal flats: combine `LAMP OFF` exposures to dark. |
| | Subtract internal dark or master dark from flat exposures. |
| | Fit slope of pixel values against illumination level. |
| | Add pixels with significant deviations to bad pixel map. |
| Output data: | `MASTER_IMG_FLAT_2RG` |
| | `BADPIX_MAP_2RG` |
| Expected accuracies: | **TBD** |
| QC1 parameters: | `QC LM MASTERFLAT RMS` |

| | |
|---|---|
| | QC LM FLAT NBADPIX<br>QC LM FLAT MEAN ##<br>QC LM FLAT RMS ## |
| hdrl function | hdrl_bpm_fit_compute<br>hdrl_imagelist_collapse<br>hdrl_imagelist_sub_image |


**Figure 9:** metis_lm_img_flat – creation of IMG_LM master flatfield.
**TODO: Include averaging of frames at same illumination**

### 5.2.2 LM-band imaging basic reduction

**New recipe – this may be too basic and could be joined with the background subtraction.**

This recipe performs the basic reduction of raw exposures from the LM-band imager, i.e. dark subtraction and flat fielding. It is used for both standard and science exposures.

Basic statistics of the images can be used to screen for saturation.

**TODO: This recipe should analyse the masked detector regions for channel offset correction and crosstalk (see [RD7]).**

| | |
|---|---|
| Recipe name: | `metis_lm_img_basic_reduce` |
| Purpose: | apply basic reduction of images |
| Type: | Calibration, Science |
| Templates: | `METIS_img_lm_cal_standard` |
| | `METIS_img_lm_*_obs_*` |
| Input data: | Dithered images (standard, science) |
| | Blank sky images (if available) |
| | Master dark |
| | Master flat |
| Matched keywords: | DIT (for dark) |
| | Filter ID (for flat) |
| Algorithm: | Subtract dark, divide by flat |
| | Analyse and remove masked regions (**TBD**) |
| Output data: | `LM_SCI_BASIC_REDUCED` |
| | `LM_STD_BASIC_REDUCED` |
| QC1 parameters: | `QC LM IMG MEDIAN` |
| | `QC LM IMG PEAK` |
| hdrl functions: | `hdrl_imagelist_sub_image` |
| | `hdrl_imagelist_div_image` |

**TODO: Figure to be done**

**Figure 10:** `metis_lm_img_basic_reduce` – basic reduction of `IMG_LM` data.

### 5.2.3 LM-band imaging background subtraction

This recipe estimates and subtracts the background from LM-band imaging data. Thermal background emission from the atmosphere, telescope and warm parts of the instrument dominate the photon count in mid-infrared observations. Accurate determination and removal of background counts is therefore crucial to make MIR data scientifically usable.

A set of observations will consist of a number of dithered exposures of the field, where the offsets are achieved using the internal chopper of METIS or the with the telescope. For extended objects, the telescope will be used to perform "out-of-field dithering", i.e. observe nearby blank patches of sky interlaced with the target observations. Imaging observations are performed in pupil-tracking mode, hence angular dithering of the field is automatic.

For in-field-dithered exposures, all dithered exposures will be averaged to obtain the background estimate. In order to only average the background contribution, an iterative procedure of object detection and masking will be employed. Averaging will be done using a robust estimator of the mean (e.g. median).

For extended objects, all out-of-field exposures will be averaged (with object rejection) and subtracted off the in-field exposures.

**TODO: Object catalogues of the target exposures could be created within this recipe or in a separate recipe. The catalogue should contain for each object: pixel coordinates ($x$, $y$), world coordinates ($\alpha$, $\delta$) based on telescope pointing and derotator information, total counts within an aperture.**

**TODO: Is this good enough for HCI images or do we need more?**

| | |
|---|---|
| Recipe name: | `metis_lm_img_background` |
| Purpose: | estimate and subtract background |
| Type: | Calibration |
| Templates: | `METIS_img_lm_cal_standard` |
| | `METIS_img_lm_*_obs_*` |
| Input data: | `LM_SCI_BASIC_REDUCED` |
| | `LM_STD_BASIC_REDUCED` |
| Matched keywords: | dither position (`SKY`? **TBD**) |
| Algorithm: | Average all or `SKY` exposures with object rejection |
| | Subtract background |
| Output data: | `LM_SCI_BKG` |
| | `LM_STD_BKG` |
| | `LM_SCI_BKG_SUBTRACTED` |
| | `LM_STD_BKG_SUBTRACTED` |
| | `LM_SCI_OBJECT_CAT` |
| | `LM_STD_OBJECT_CAT` |
| QC1 parameters: | `QC LM IMG BKG MEDIAN` |
| hdrl functions: | `hdrl_imagelist_sub_image` |
| | `hdrl_imagelist_div_image` |
| | `hdrl_catalogue_compute` |

TODO: Figure to be done

**Figure 11:** metis_lm_img_background – background estimation and subtraction of dithered IMG_LM data.

### 5.2.4 LM-band imaging photometric standard analysis

This recipe determines the conversion from ADU to physical units from a set of reduced exposures of a photometric standard star. The flux of the star is measured in each exposure in ADU, normalised to an exposure time of 1 second and averaged over all exposures. In addition, the exposures are stacked (after recentering on the standard star, but without derotation) and the flux is measured in the combined image. Comparison to the tabulated brightness of the star in the observing filter yields the conversion factor from ADU $s^{-1}$ to photons $s^{-1}$.

QC parameter will include estimates of the sensitivity for the detection of point sources and surface brightness sensitivity following [RD8].

| | |
|---|---|
| Name: | metis_lm_img_std_process |
| Purpose: | Determine conversion factor between detector counts and physical source flux |
| Type: | Calibration |
| Templates: | METIS_img_lm_cal_standard |
| Input data: | LM_STD_BKG_SUBTRACTED |
| | photometric standard catalogue |
| Matched keywords: | OBJECT ID |
| | FILTER ID |
| Recipe parameters: | None (TBD) |
| Algorithm: | Measure flux from star in detector units |
| | Compute conversion factor to physical units |
| | Measure background noise (std. dev.) and compute detection limits. |
| Output data: | LM_STD_COMBINED |
| | FLUXCAL_TAB |
| Expected accuracies: | **TBD** |
| QC1 parameters: | QC LM IMG STD BACKGD RNS |
| | QC LM STD PEAK CNTS |
| | QC LM STD APERTURE CNTS |
| | QC LM STD STREHL |
| | QC LM STD FLUXCONV |
| | QC LM STD AIRMASS |
| | QC LM SENSITIVITY |
| | QC LM AREA SENSITIVIY |
| hdrl function: | hdrl_strehl_compute |
| | hdrl_catalogue_compute |
| | hdrl_efficiency_compute |
| | hdrl_imagelist_collapse |

TODO: Figure to be done

**Figure 12:** `metis_lm_img_std_process` – compute conversion between ADU and physical flux units

### 5.2.5 LM-band imaging calibration

This recipe applies the flux calibration to the reduced science images and adds geometric calibration data to the FITS header. The products of this recipe are fully calibrated individual exposures.

Each image is multiplied by the conversion factor such that pixel values are in units of photons $s^{-1}$. The header of each file receives keyword `BUNIT` with value `'ph / s'`.

**TODO: Other units may be possible, although additional information is needed. For instance, `'ph / (s arcsec2)'` makes values independent of the pixel scale, but requires a distortion map (variation of pixel scale across the detector). Energy units (erg instead of photons) require knowledge of the spectral energy distribution of the sources, in particular for broad-band filters.**

LM-band imaging observations will be performed in pupil-tracking mode [RD1], which means that the field rotates from exposure to exposure. The information about the field orientation along with target coordinates, pixel scale and higher-order polynomial distortion coefficients is written to the FITS header. The images are not resampled by this recipe, this is left to `metis_lm_img_sci_postprocess`.

| | |
|---|---|
| Name: | `metis_lm_img_calibrate` |
| Purpose: | Convert science images to physical units<br>Add distortion information |
| Type: | Calibration |
| Templates | |
| Input data: | `LM_SCI_BKG_SUBTRACTED`<br>`FLUXCAL_TAB`<br>`LM_DISTORTION_TABLE` |
| Matched keywords: | Filter ID |
| Recipe parameters: | None (TBD) |
| Algorithm: | Scale image data to ph/s<br>Add header information (`BUNIT`, WCS, etc.) |
| Output data: | `LM_SCI_CALIBRATED` |
| QC1 parameters: | None |
| hdrl functions: | `hdrl_imagelist_mult_scalar` |

**TODO: Figure to be done**

**Figure 13:** `metis_lm_img_calibrate` – convert images to physical flux units

### 5.2.6 LM-band imaging post-processing

This recipe coadds a sequence of flux-calibrated, background-subtracted images (possibly from several observing blocks) after resampling the images on a common pixel grid defined by a standard sky projection. The alignment of the images (`CRVAL` keywords, rotation) may have to be checked and refined through cross-correlation of the overlapping images (TBC). The number of input images contributing to any pixel in the output image (variable due to dither offsets and bad pixels) will be documented in a contribution map.

This recipe will only be used in the science-grade pipelines, not at the observatory.

| | |
|---|---|
| Name: | `metis_lm_img_sci_postprocess` |
| Purpose: | Coadd reduced images. |
| Requirements: | METIS-6104 |
| Templates: | — |
| Type: | Science |
| Input data: | Calibrated science images (`LM_SCI_CALIBRATED`) |
| | Associated bad-pixel maps (`LM_SCI_BADPIX`) |
| Parameters: | None (TBD). |
| Algorithm: | Check and refine WCS of input images by cross-correlation (on object catalogue or on image). |
| | Determine output pixel grid encompassing all input images. |
| | Resample images to output pixel grid. |
| | Coadd. |
| Output data: | `LM_SCI_COADD` (coadded, mosaiced image) |
| | `LM_SCI_COADD_ERROR` (coadded, mosaiced error image) |
| | `LM_SCI_COADD_CONTRIB` (contribution map) |
| Expected accuracies: | TBD |
| QC1 parameters: | `QC LM SCI NEXPOSURE` |


**Figure 14:** `metis_lm_img_sci_postprocess` – post-processing (coaddition) of reduced `IMG_LM` science frames.

### 5.2.7 LM-band imaging distortion calibration

Calibration of the imaging distortion is done on an image of a pin-hole grid mask located in a focal plane within the instrument. The distortion is described in terms of a polynomial model whose coefficients can be transformed to WCS keywords and applied to any other pipeline product. In addition to the distortion table, a map of pixel scale across the detector will be created.

| | |
|---|---|
| Name: | metis_lm_img_distortion |
| Purpose: | Determine optical distortion coefficients for the LM imager. |
| Requirements: | METIS-6087 |
| Templates: | METIS_img_lm_cal_distortion |
| Type: | Calibration |
| Input data: | Images of grid mask in WCU-FP2 or CFO-FP2. |
| | Image with WCU window closed (background) |
| Parameters: | TBD |
| Algorithm: | Subtract background image. |
| | Measure location of point source images in frames. |
| | Fit polynomial coefficients to deviations from grid positions. |
| Output data: | LM_DISTORTION_TABLE (table with polynomial coefficients) |
| | LM_DISTORTION_MAP (pixel scale across detector) |
| | LM_DIST_REDUCED (reduced grid mask images) |
| Expected accuracies: | TBD |
| QC1 parameters: | QC LM DISTORT RMS |
| hdrl functions: | hdrl_catalogue_create |


**Figure 15:** `metis_lm_img_distortion` – LM IMG distortion calibration

## 5.3 N-band imaging

### 5.3.1 N-band imaging flatfield

The purpose of the flat-field calibration is to determine pixel-to-pixel gain variations and large scale illumination variations (due to inhomogeneities of optical elements in the telescope or instrument). Calibration frames are obtained either during day time using the black-body lamp of the WCU (internal flats) or by taken images of the twilight sky (twilight flats). Advantages and disadvantages of the two types of flat are discussed in [RD5].

MIR detectors are typically unstable in that they show gain fluctuations on rather short time scales, hence science exposures may have a different flat-field structure from those captured by the calibration flats. While the GeoSnap detector is expected to be more stable than the AQUARIUS detector, its stability properties need to be studied further in order to assess whether science images can be flat fielded. N-band flat fields will be taken in any case for quality control and monitoring purposes.

Since the operational concept for twilight flats needs to be refined during commissioning at the telescope, the current recipe design is primarily valid for internal flats.

This recipe creates a master flat for the GeoSnap detector (N-band imaging) from lamp or sky images matched by various setup parameters as detailed below. A set of internal flats includes a number of exposures with `LAMP OFF`, which will be used for dark subtraction. For twilight flats a master dark will be subtracted. The master flat is obtained by the slope of a linear fit of the pixel values against the illumination level of the exposures.

The quality control parameters give various statistics for each input frame (mean, standard deviation, etc.), the standard deviation of the normalised master flat and the number of bad pixels identified by the recipe. If a bad-pixel map is provided on input, it is updated, otherwise a new one is created.

| | |
|---|---|
| Name: | `metis_n_img_flat` |
| Purpose: | Create master flat field for the N-band imaging detector. |
| Requirements: | METIS-6098 |
| Type: | Calibration |
| Templates: | `METIS_img_n_cal_LampFlat` |
| | `METIS_all_cal_TwilightFlat` |
| Input data: | Flat field images taken with lamp or sky. |
| | Master dark (for twilight flats) |
| | Bad pixel map |
| Matched keywords: | Detector ID |
| | Filter ID |
| | ADC ID |
| | possibly others (e.g. coronagraphic mask, **TBD**) |
| Recipe parameters: | Combination method (`mean`, `median`, `sigclip`, ...) |
| | Parameters for combination methods |
| | Threshold for bad-pixel identification |
| Algorithm: | For internal flats: combine `LAMP OFF` exposures to dark. |
| | Subtract internal dark or master dark from flat exposures. |
| | Fit slope of pixel values against illumination level. |
| | Add pixels with significant deviations to bad pixel map. |

| | |
|---|---|
| Output data: | MASTER_IMG_FLAT_GEO |
| | BADPIX_MAP_GEO |
| Expected accuracies: | **TBD** |
| QC1 parameters: | QC N MASTERFLAT RMS |
| | QC N FLAT NBADPIX |
| | QC N FLAT MEAN ## |
| | QC N FLAT RMS ## |
| hdrl function | hdrl_bpm_fit_compute |
| | hdrl_imagelist_collapse |
| | hdrl_imagelist_sub_image |

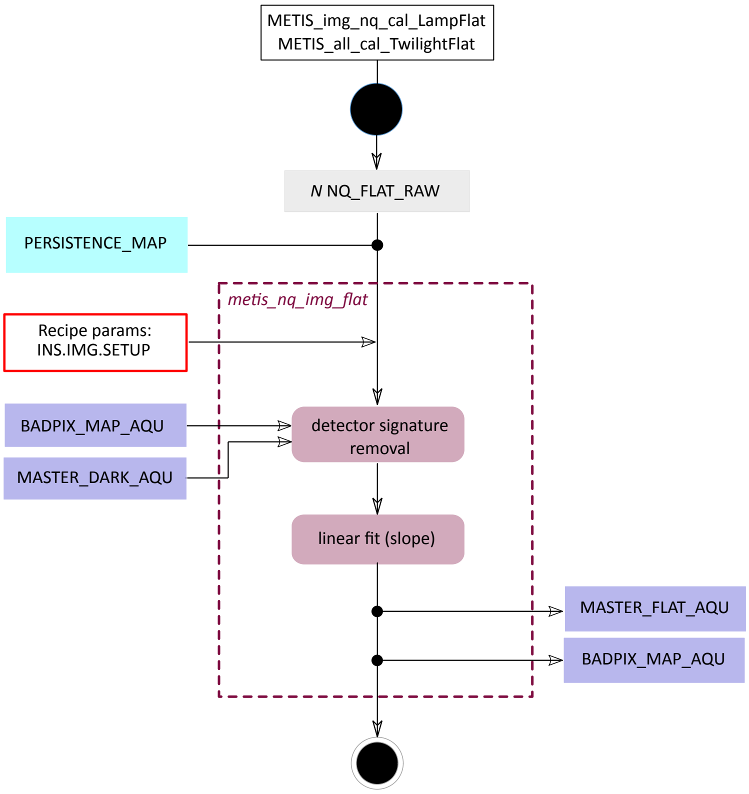



**Figure 16:** `metis_n_img_flat` – creation of `IMG_N` master flatfield
**TODO: Update ('nq' to 'n')**

### 5.3.2 N-band imaging chop-nod combination

This recipe combines a set of exposures taken at all positions of a defined chop-nod pattern and adds/subtracts them into a single chop/nod difference image. Depending on the actual chop-nod pattern, this image will contain one or more positive and negative beams.

If flat fielding proves feasible and useful for the GeoSnap detector the master flat can be applied. If no jitter is applied, i.e. if the beam is at the same detector position for all exposures taken at a given chop position, then the master flat can be divided into the final chop-nod difference image. Otherwise, the master flat will have to be divided into the chop half-cycle images before the jitter correction is applied.

| | |
|---|---|
| Name: | metis_n_img_chopnod |
| Purpose: | chop/nod combination of exposures for background subtraction |
| Type: | Calibration, Science |
| Templates: | METIS_img_nq_cal_standard |
| | METIS_img_n_obs_AutoChopNod |
| | METIS_img_n_obs_GenericChopNod |
| | METIS_img_n_cvc_obs_AutoChop |
| | METIS_img_n_clc_obs_FixedSkyOffset |
| | METIS_img_n_cal_psf |
| Input data: | Chopped/nodded science or standard images |
| | Bad-pixel map |
| Matched keywords: | Filter ID |
| | Chop position |
| | Nod position |
| Recipe parameters: | TBD |
| Algorithm: | Add/subtract images to subtract background |
| Output data: | N_SCI_BKG_SUBTRACTED |
| | N_STD_BKG_SUBTRACTED |
| QC1 parameters: | N IMG PEAK CNTS |
| hdrl functions: | hdrl_imagelist_collapse |

TODO: Figure to be done

**Figure 17:** metis_n_img_chopnod – Combination of chop/nodded images.

### 5.3.3 N-band imaging photometric standard analysis

This recipe determines the conversion from ADU to physical units from a chop-nod difference image of a photometric standard star. The flux of the standard star is measured in each of the beams of the chop-nod difference image, averaged and normalised to an exposure time of 1 second. Comparison to the tabulated brightness of the star in the observing filter yields the conversion factor from $\mathrm{ADU\,s^{-1}}$ to $\mathrm{photons\,s^{-1}}$.

QC parameters will include estimates of the sensitivity for the detection of point sources and surface brightness sensitivity following [RD8].

| | |
|---|---|
| Name: | `metis_n_img_std_process` |
| Purpose: | Determine conversion factor between detector counts and physical source flux. |
| Type: | Calibration |
| Templates: | `METIS_img_n_cal_standard` |
| Input data: | `N_STD_BKG_SUBTRACTED` |
| | photometric standard catalogue |
| Matched keywords: | Object ID |
| | Filter ID |
| Recipe parameters: | None (TBD) |
| Algorithm: | Create object catalogue, identify standard star |
| | Measure flux from star in all beams |
| | Compute conversion factor to physical units |
| | Measure background noise (rms) and compute detection limits. |
| Output data: | `FLUXCAL_TAB` |
| Expected accuracies: | **TBD** |
| QC1 parameters: | `QC N STD PEAK CNTS` |
| | `QC N STD APERTURE CNTS` |
| | `QC N STD STREHL` |
| | `QC N STD FLUXCONV` |
| | `QC N STD AIRMASS` |
| | `QC N SENSITIVITY` |
| | `QC N AREA SENSITIVITY` |
| hdrl functions: | `hdrl_catalogue_create` |
| | `hdrl_strehl_compute` |

**TODO: Figure to be done**

**Figure 18:** `metis_n_img_std_process` – compute conversion between ADU and physical flux units.

### 5.3.4 N-band imaging calibration

This recipe applies the flux calibration to the chop-nod difference image. A unique geometric calibration is not possible at this point, although one could take one of the beams (e.g. the positive beam in a parallel two-point chop-nod pattern) as reference for a WCS. Distortion information can be added without a reference point as it pertains to the detector/focal plane, not to the field.

The products of this recipe is the fully calibrated chop-nod difference image.

The image is multiplied by the conversion factor such that pixel values are in units of photons $s^{-1}$. The header receives the keyword `BUNIT` with value `'ph / s'`.

| | |
|---|---|
| Name: | `metis_n_img_calibrate` |
| Purpose: | Convert science image to physical units |
| | Add distortion information |
| Type: | Calibration |
| Templates: | |
| Input data: | `N_SCI_BKG_SUBTRACTED` |
| | `FLUXCAL_TAB` |
| | `N_DISTORTION_TABLE` |
| Matched keywords: | Filter ID |
| Recipe parameters: | TBD |
| Algorithm: | Scale image data to ph/s |
| | Add header information (`BUNIT`, WCS, etc.) |
| Output data: | `N_SCI_CALIBRATED` |
| QC1 parameters: | None |

TODO: Figure to be done

**Figure 19:** `metis_n_img_calibrate` – convert image to physical flux units

### 5.3.5 N-band imaging restoration

This recipe attempts to combine the positive and negative beams of the chop-nod difference image into a single positive image of the source. For compact sources with a size smaller than half the distance between the beams, it suffices to cut out small regions around the source images and add the with the appropriate signs to obtain a single image.

Algorithms for image restoration of extended sources exist but it remains **TBD** whether these are sufficiently simple and robust to be included in the pipeline (cf. Sect. 8.8 of [AD1]).

| | |
|---|---|
| Name: | `metis_n_img_restore` |
| Purpose: | Restore a single positive beam from chop-nod difference image |
| Type: | Science |
| Input data: | `N_SCI_CALIBRATED` |
| Recipe parameters: | size of cutout region |
| Algorithm: | Cut regions around beams |
| | Add regions with appropriate signs |
| Output data: | `N_SCI_RESTORED` |
| QC1 parameters: | None |
| hdrl functions: | `hdrl_imagelist_collapse` |

**TODO: Figure to be done**

**Figure 20:** `metis_n_img_restore` – Create a single positive image from chop-nod difference image

### 5.3.6 N-band imaging distortion calibration

Calibration of the imaging distortion is done on an image of a pin hole mask located in a focal plane within the instrument. The distortion is described in terms of a polynomial model whose coefficients can be transformed to WCS keywords and applied to any other pipeline product. In addition to the distortion table, a map of pixel scale across the detector will be created.

| | |
|---|---|
| Name: | `metis_n_img_distortion` |
| Purpose: | Determine optical distortion coefficients for the N imager. |
| Templates: | `METIS_img_n_cal_distortion` |
| Type: | Calibration |
| Input data: | Images of grid mask in WCU-FP2 or CFO-FP2. |
| | Image with WCU window closed (background). |
| | Bad pixel map |
| Parameters: | TBD |
| Algorithm: | Subtract background image. |
| | Measure location of point source images in frames. |
| | Fit polynomial coefficients to deviations from grid positions. |
| Output data: | `N_DISTORTION_TABLE` (table with polynomial coefficients) |
| | `N_DISTORTION_MAP` (pixel scale across detector) |
| | `N_DIST_REDUCED` (reduced grid mask images) |
| Expected accuracies: | TBD |
| QC1 parameters: | `QC N DISTORT RMS` |
| hdrl functions: | `hdrl_catalogue_create` |


**Figure 21:** `metis_n_img_distortion` – `IMG_N` distortion calibration

## 5.4 Long-slit spectroscopy, LM band

A draft of the reduction cascade is shown in Fig. 4 together with the data processing table (Table 3). The first part concerns the detector calibrations, which are independent of the observing mode and described in Section 5.1. This affects the dark correction, linearity and gain determination and bad pixel detection. The second step is the spectroscopic flatfielding (i.e. the determination and application of the Relative Spectral Response Function (RSRF)), followed by the wavelength correction and the determination of the response curve for the flux calibration. Subsequently, the main reduction is conducted, which applies the previously created master calibration files to the science frames. Finally, the telluric absorption correction is applied using the modelling approach with `molecfit`.

Special emphasis has to be drawn to the effects of the Earth's atmosphere in several respects:

- Wavelength calibration: Absorption/emission features are intended to be used for the wavelength calibration. Thus, a good knowledge on / identification of these features is crucial for the accuracy of the wavelength calibration.
- Telluric correction: In the MIR regime telluric absorption is one of the most dominant effects visible in spectra. Modelling approaches like `molecfit` heavily rely on accurate atmospheric input profiles, which represent the actual state and composition of the Earth's atmosphere. This especially applies to the Precipitable Water Vapour (PWV) content since this is the most dominant and most variable species.
- Atmospheric dispersion: Mid-infrared E-ELT Imager and Spectrograph (METIS) will have Atmospheric Dispersion Corrector (ADC)s compensating the effect of atmospheric dispersion. However, for technical reasons these ADCs are fixed at several positions. This means that the compensation is only partially. This leads to two practical effects: (a) wavelength-dependent slit losses, and (b) distortions in both, the spatial and the spectral direction (see [RD9] for more details). For both, the pipeline needs to correct for. Since airmass, ambient temperature/pressure, slit orientation, and the properties of the ADCs are known, the only required parameter to be determined for the compensation is the PWV.

It is therefore crucial to have a radiometer (e.g. L-HATPRO) available at the Extremely Large Telescope (ELT), which provides direct measurements of the PWV along the observation direction.

### 5.4.1 Recipes `metis_det_lingain` and `metis_det_dark`

These recipes are described in Section 5.1.

### 5.4.2 LM-LSS Flatfielding recipe `metis_LM_lss_rsrf`:

**TODO: Not yet revised (see [AD1])**

### 5.4.3 LM-LSS wavelength calibration recipe `metis_LM_lss_wave`:

This recipe aims at deriving a first guess solution for the wavelength calibration on basis of the WCU Quantum Cascade Laser (QCL) (c.f. [RD5]). Therefore the first steps are the removal of the detector signature of the `LM_WAVE_RAW` frames by applying the master calibration files derived in the previous steps, following by the background subtraction (if needed, TBD) and the application of the RSRF. The distortion of the lines (i.e. possible tilt, curvature,...) and the wavelength solution is determined by the algorithm described in Sect. 8.5 in [AD1] and in [RD5]. The reference frame is defined by the QCL line catalogue (`QLC_LINE_CAT`).

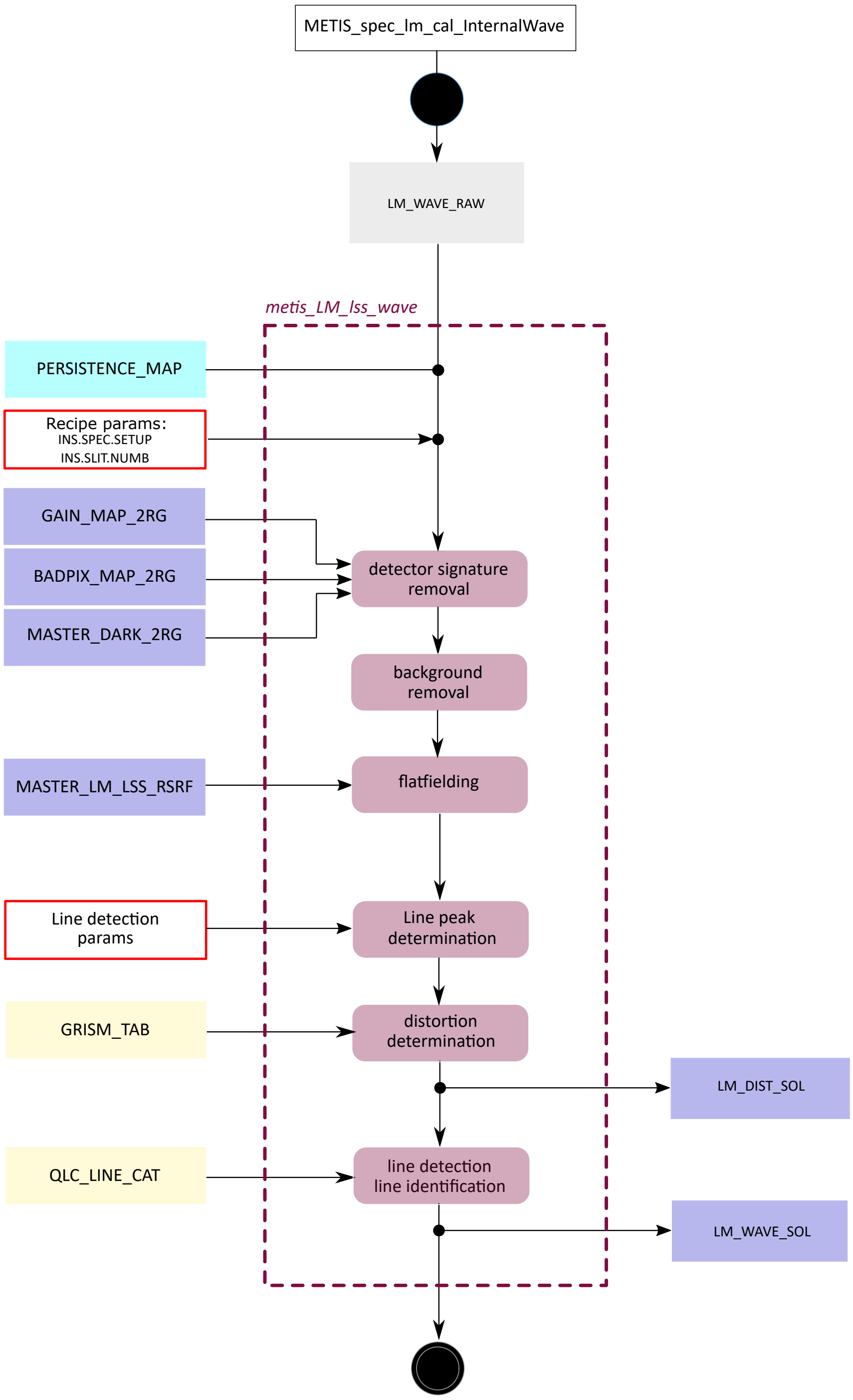



**Figure 22:** `metis_LM_lss_wave` – Creation of the LM LSS master wavelength correction.

| | |
|---|---|
| Name: | metis_LM_lss_wave |
| Purpose: | Wavelength calibration |
| Type: | Calibration |
| Requirements: | METIS-6084, METIS-1371, METIS-6074 |
| Observing templates: | MMETIS_spec_lm_cal_internalwave, |
| Input data: | raw QCL spectra (LM_WAVE_RAW) |
| | WCU grid for first guess distortion correction (TBD) |
| | WCU lamp spectrum for first guess wavelength solution (TBD) |
| | PERSISTENCE_MAP |
| | GAIN_MAP_2RG |
| | MASTER_DARK_2RG |
| | BADPIX_MAP_2RG |
| | MASTER_LM_LSS_RSRF |
| | GRISM_TAB |
| | QLC_LINE_CAT |
| Parameters: | (TBD) |
| Algorithm: | Application of detector master calibration files |
| | Determination and application of the distortion correction |
| | Determination and application of the first guess of the wavelength solution |
| Output data: | LM_DIST_SOL (PRO.CATG=LM_DIST_SOL): Distortion solution |
| | LM_WAVE_SOL (PRO.CATG=LM_WAVE_SOL): Wavelength solution |
| Expected accuracies: | (TBD) |
| QC1 parameters: | TBD: TBD |

### 5.4.4 LM-LSS flux calibration recipe metis_LM_lss_flux:

Spectrophotometric standard stars calibration: As first step the detector master calibration files derived previously are applied followed by the background subtraction, if needed the distortion correction (LM_DIST_SOL), and the wavelength calibration by means of the first guess solution (LM_WAVE_SOL) and the telluric sky lines (c.f. Sect. 8.5 in [AD1]). Then the recipe extracts the standard star spectrum object, removes sky lines, collapses the 2D to 1D spectra and applies a telluric correction in an automated way to the standard star spectrum (in contrast to the science observations, which are telluric corrected in a dedicated recipe to achieve the best correction). The response curve is obtained by comparing the extracted spectrum with a model and/or another reference spectrum of the standard star.


**Figure 23:** `metis_LM_lss_flux` – Flux calibration recipe.

| | |
|---|---|
| Name: | metis_LM_lss_flux |
| Purpose: | Flux calibration |
| Type: | Calibration |
| Requirements: | METIS-6084, METIS-6074 |
| Observing templates: | METIS_spec_lm_acq,<br>METIS_spec_lm_cal_lampwave<br>METIS_spec_lm_cal_AutoNodOnSlit,<br>METIS_spec_lm_obs_GenericOffset<br>METIS_spec_lm_cal_standard<br>METIS_spec_lm_cal_slit_adc |
| Input data: | raw spectrophotometric STANDARD star data (LM_FLUX_RAW)<br>PERSISTENCE_MAP<br>GAIN_MAP_2RG<br>BADPIX_MAP_2RG<br>MASTER_DARK_2RG<br>MASTER_LM_LSS_RSRF<br>LM_DIST_SOL<br>LM_WAVE_SOL<br>AO_PSF_MODEL<br>ATM_LINE_CAT<br>HITRAN, LSF_KERNEL, ATM_PROFILE<br>REF_FLUX_CAT |
| Parameters: | (TBD) |
| Algorithm: | Application of master calibration files<br>Background removal<br>Determination and application of the distortion correction<br>Determination and application of the wavelength solution<br>Identifying/separatiing sky/object pixels<br>Removing sky lines: Creation and Subtraction of 2D sky<br>Collapsing 2D to 1D spectrum, (see Fig. 24)<br>Determination and application of response curve |
| Output data: | LM_STD_OBJ_MAP: Pixel map of object pixels<br>LM_STD_SKY_MAP: Pixel map of sky pixels<br>LM_STD_1D: coadded, wavelength calibrated, collapsed 1D spectrum<br>INSTR_RESPONSE: response function (TBD) |
| Expected accuracies: | (TBD) |
| QC1 parameters: | QC LM LSS STD BACKGD MEAN: Mean value of background<br>QC LM LSS STD BACKGD MEDIAN: Median value of background<br>QC LM LSS STD BACKGD SIGMA: Sigma value of background<br>QC LM LSS STD SNR: Signal-to-noise ration of flux standard star spectrum |

QC LM LSS STD SNRNOISE: Noise level of flux standard star spectrum

QC LM LSS STD FWHM: FWHM of flux standard spectrum

LM LSS FLUX: (TBdef)

QC LM LSS FLUX WAVECAL DEVMEAN: Mean deviation from the wavelength reference frame (TBDef)

QC LM LSS FLUX WAVECAL FWHM: Measured FWHM of lines

QC LM LSS FLUX WAVECAL NIDENT: Number of identified lines

QC LM LSS FLUX WAVECAL NMATCH: Number of lines matched between catalaogue and spectrum

QC LM LSS FLUX WAVECAL POLYDEG: Degree of the polynomial

QC LM LSS FLUX WAVECAL POLYCOEFF<n>: *n*-th coefficient of the polynomial

QC LM LSS FLUXCAL SNR: Signal-to-noise ration of flux standard star spectrum

QC LM LSS FLUXCAL SNRNOISE: Noise level of flux standard star spectrum

QC LM LSS FLUXCAL FWHM: FWHM of flux standard spectrum

QC LM LSS FLUXCAL PSFLOSS: percentage of AO induced slit losses (TBdef)

### 5.4.5 LM-LSS science reduction recipe `metis_LM_lss_sci`:

The science calibration recipe comprises the extraction of the object (i.e. separation of object/sky pixels), removing the sky lines, the application of the response curve previously defined, the 2D to 1D collapse and the coaddition. In contrast to the flux standard star reduction, the telluric correction on the science data is done in a dedicated recipe afterwards to achieve best quality for the correction.

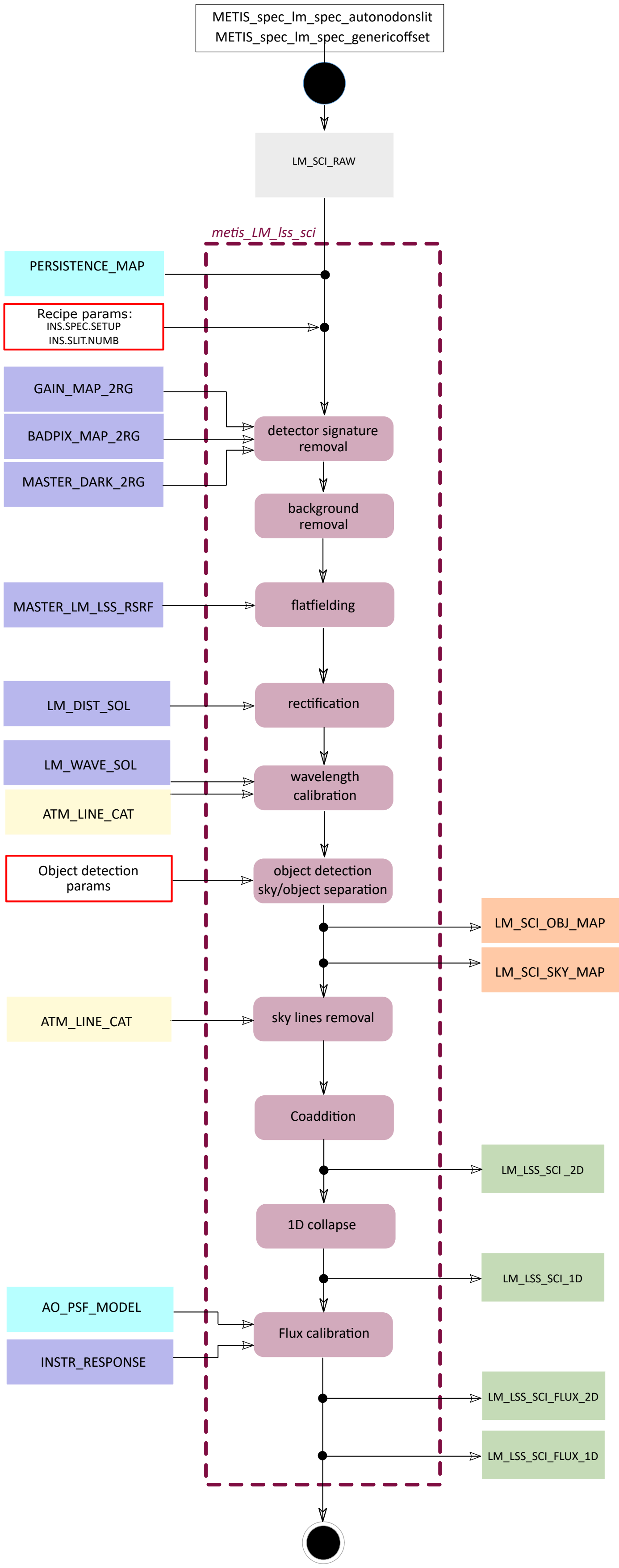



**Figure 24:** `metis_LM_lss_sci` – Science reduction recipe.

| | |
|---|---|
| Name: | metis_LM_lss_sci |
| Purpose: Science data calibration | |
| Type: | Science reduction |
| Requirements: | METIS-6084 |
| Observing templates: | METIS_spec_lm_acq,<br>METIS_spec_lm_obs_AutoNodOnSlit,<br>METIS_spec_lm_obs_GenericOffset<br>METIS_spec_lm_cal_slit_adc |
| Input data: | LM_LSS_SCI_WAVE |
| Input data: | raw SCIENCE data (LM_SCI_RAW)<br>PERSISTENCE_MAP<br>GAIN_MAP_2RG<br>BADPIX_MAP_2RG<br>MASTER_DARK_2RG<br>MASTER_LM_LSS_RSRF<br>LM_DIST_SOL<br>LM_WAVE_SOL<br>ATM_LINE_CAT<br>AO_PSF_MODEL<br>INSTR_RESPONSE |
| Parameters: | (TBD) |
| Algorithm: | Application of the detector master calib files<br>wavelength calibration<br>Identifying/separatiing sky/object pixels<br>Removing sky lines: Creation and Subtraction of 2D sky<br>Coaddition of individual object spectra of one OB<br>Collapsing 2D to 1D spectrum, (see Fig. 24)<br>Application of the response function (flux calibration) |
| Output data: | LM_SCI_OBJ_MAP: Pixel map of object pixels<br>LM_SCI_SKY_MAP: Pixel map of sky pixels<br>LM_LSS_SCI_2D: coadded, wavelength calibrated 2D spectrum<br>(PRO_CATG: LM_LSS_2d_coadd_wavecal)<br>LM_LSS_SCI_1D: coadded, wavelength 1D spectrum<br>(PRO_CATG: LM_LSS_1d_coadd_wavecal)<br>LM_LSS_SCI_FLUX_2D: coadded, wavelength calibrated 2D spectrum<br>(PRO_CATG: LM_LSS_2d_coadd_wavecal)<br>LM_LSS_SCI_FLUX_1D: coadded, wavelength 1D spectrum<br>(PRO_CATG: LM_LSS_1d_coadd_wavecal) |
| Expected accuracies: | (TBD) |
| QC1 parameters: | QC LM LSS SCI SNR: Signal-to-noise ration of science spectrum |

QC LM LSS SCI SNRNOISE: Noise level of science spectrum

QC LM LSS SCI FLUX SNR: Signal-to-noise ration of flux calibrated science spectrum

QC LM LSS SCI FLUX SNRNOISE: Noise level of flux calibrated science spectrum

LM LSS SCI: (TBdef)

QC LM LSS SCI WAVECAL DEVMEAN: Mean deviation from the wavelength reference frame (TBDef)

QC LM LSS SCI WAVECAL FWHM: Measured FWHM of lines

QC LM LSS SCI WAVECAL NIDENT: Number of identified lines

QC LM LSS SCI WAVECAL NMATCH: Number of lines matched between catalaogue and spectrum

QC LM LSS SCI WAVECAL POLYDEG: Degree of the polynomial

QC LM LSS SCI WAVECAL POLYCOEFF<n>: $n$-th coefficient of the polynomial

### 5.4.6 LM-LSS telluric correction recipe metis_LM_lss_tac:

**TODO: Not yet revised (see [AD1])**

## 5.5 LM integral-field spectroscopy (LMS)

**TODO: This section is identical to the PDR document [AD1]. We will consider rearranging the recipes to be in line with the imaging pipelines. This would entail handling basic reduction and background subtraction for of both science and standard exposures in common recipes (`metis_lms_basic`, `metis_lms_background`), then having a recipe to analyse the standard observations (`metis_lms_photstd`). The science exposures are then fully calibrated (`metis_lms_calibrate`). A full set of exposures would then be assembled and restored with a fully sampled PSF in a post-processing recipe (`metis_lms_combine`).**

### 5.5.1 LMS wavelength calibration

This recipe processes daytime wavelength calibration images to derive the pixel-to-wavelength relation for the LM integral-field spectrograph. The calibration template will use the quantum cascade laser (QCL) in the warm calibration unit to finely sample the desired wavelength range. The image will consist of lines for each wavelength and slice. The solution will have to provide for each detector pixel $(x,y)$ the slice number $i$, the spatial position $\xi$ along the slice and the wavelength in the dispersion correction. As the slices and wavelength lines may be tilted with respect to the detector columns and rows, a combined solution is required

$$\xi = f_i(x,y) \quad (1)$$
$$\lambda = g_i(x,y) \quad (2)$$

The boundaries of the slice image on the detector are obtained by measuring the left and right edges of the wavelength lines and interpolating. The slice number is then obtained by counting the slices according to the optical design of the spectrograph. The wavelength of each line is known from the settings of the QCL, the $x$ coordinate is obtained by linear interpolation along the line (or perhaps using the distortion table from `metis_lms_distortion` if necessary). The functions $f_i$ and $g_i$ are expected to be sufficiently accurately described by low-order polynomials.

The recipe produces a multi-extension FITS file with an image extension mapping wavelength across each detector in the array. A table extension holds the polynomial coefficients.

| | |
|---|---|
| Name: | `metis_lms_wavecal` |
| Purpose: | Determine pixel-to-wavelength transformation. |
| Requirements: | METIS-6074 |
| Type: | Calibration |
| Templates: | `METIS_ifu_cal_LampWave` |
| Input data: | Images taken with WCU QCL source |
| | Master dark |
| | Bad-pixel map |
| | Distortion table (TBD) |
| Parameters: | TBD |
| Algorithm: | Measure line locations (left and right edges, centroid by Gaussian fit) |
| | Compute wavelength solution $\xi(x,y,i)$, $\lambda(x,y,i)$ |
| Output data: | `LMS_WAVECAL` |
| Expected accuracies: | TBD |
| QC1 parameters: | `QC LMS WAVECAL RMS` |
| | `QC LMS WAVECAL NLINES` |

QC LMS WAVECAL PEAK CNTS
QC LMS WAVECAL LINE WIDTH

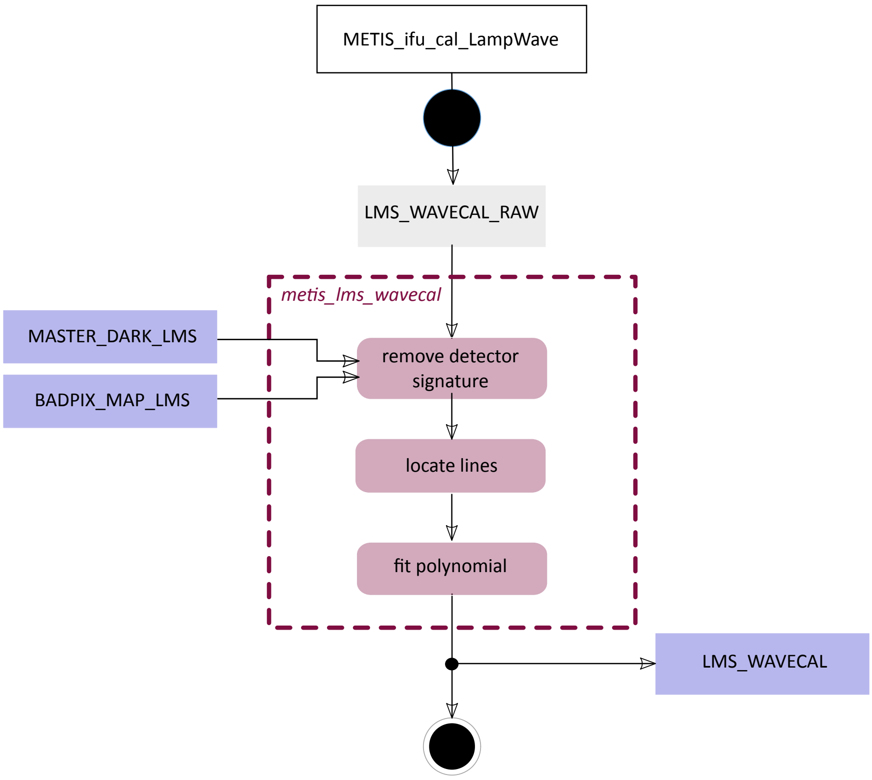



**Figure 25:** `metis_lms_wavecal` – daytime wavelength calibration for the LMS.

### 5.5.2 LMS relative spectral response function

This recipe creates a spectroscopic master flat and determines the relative spectral response function (RSRF) for the four HAWAII2RG detectors of the LM spectrograph. The input data are obtained by illuminating the field of view with the black-body calibration lamp at two different temperatures. The RSRF is then determined by dividing the image by the known lamp continuum shape for the respective temperature. We refer to the two-dimensional image obtained by this division as `MASTER_FLAT` and the one-dimensional reponse function obtained by averaging at constant wavelength as `RSRF`. The bad pixel mask can be updated by identifying pixels that deviate strongly from their neighbours.

| | |
|---|---|
| Name: | `metis_lms_rsrf` |
| Purpose: | Create relative spectral response function for the LMS detector. |
| Requirements: | METIS-6131, METIS-6698 |
| Type: | Calibration |
| Templates: | `METIS_ifu_cal_rsrf` |
| Input data: | Raw flats taken with black-body calibration lamp. |
| | `MASTER_DARK_LMS` |
| | `BADPIX_MAP_LMS` |
| | `LMS_WAVECAL`: image with wavelength at each pixel. |
| Parameters: | TBD |
| Algorithm: | Create continuum image by mapping Planck spectrum at $T_{\mathrm{lamp}}$ to wavelength image. |
| | Divide exposures by continuum image. |
| | Average exposures to yield master flat (2D RSRF). |
| | Average in spatial direction to obtain relative response function |
| Output data: | `MASTER_FLAT_LMS` |
| | `RSRF_LMS` |
| | `BADPIX_MAP_LMS` |
| Expected accuracies: | TBD |
| QC1 parameters: | `QC LMS RSRF NBADPIX` |
| | (more TBD) |

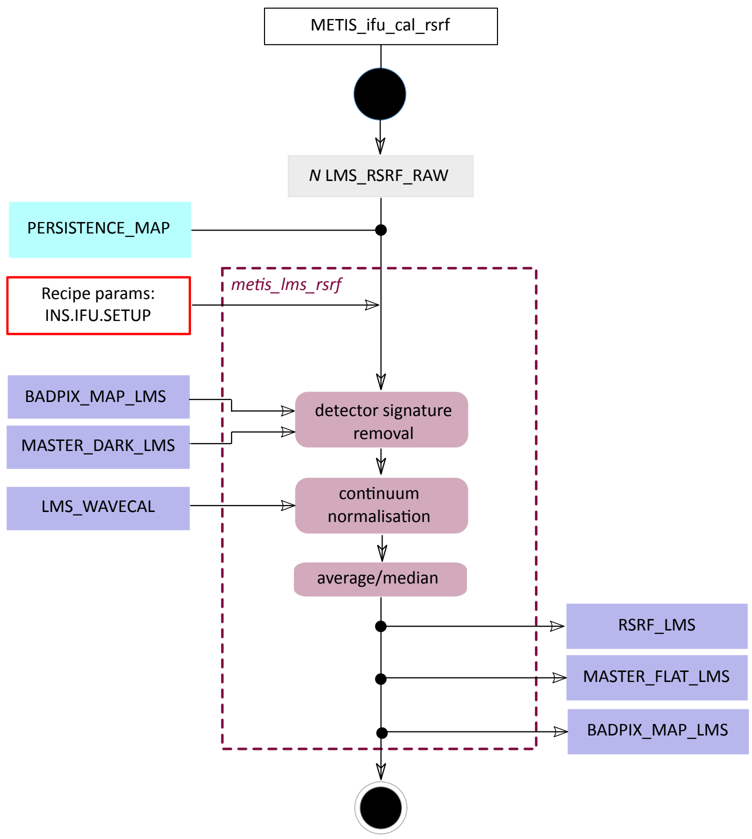



**Figure 26:** `metis_lms_rsrf` – creation of LMS relative spectral response function.

### 5.5.3 LMS flux standard reduction

This recipe reduces and analyses a series of LMS observations of a spectroscopic flux standard star. The comparison of the measured detector counts (ADU) with the tabulated spectrum of the star gives the wavelength-dependent conversion from ADU to physical units (photons per second per wavelength bin per spatial bin).

The level of stray light is estimated in the dark areas between the spectra and subtracted from the entire frame. The distribution of stray light across the field can only be characterised once the instrument is built. It is to be hoped that subtraction of a constant or a low-level 2D polynomial fit will be sufficient.

The sky and thermal background is estimated from blank sky observations (if obtained during the observing sequence) or by combining the (dithered) science frames.

The wavelength calibration is taken from the daylight calibration. It may be refined by measuring telluric emission and/or absorption lines (by fitting with `molecfit`).

| | |
|---|---|
| Name: | `metis_lms_std_process` |
| Purpose: | Determine conversion between detector counts and physical source flux. |
| Requirements: | METIS-6131 |
| Type: | Calibration |
| Templates: | `METIS_ifu_cal_standard` |
| Input data: | Raw spectra of flux standard star |
| | Master dark |
| | Master flat (2D relative spectral response function) |
| | Bad pixel mask |
| | Wavelength calibration image |
| | Distortion table |
| Parameters: | TBD |
| Algorithm: | Subtract dark, divide by master flat |
| | Estimate stray light and subtract |
| | Estimate background and subtract |
| | Rectify spectra and assemble cube |
| | Extract 1D spectrum of star |
| | Compute and apply telluric correction |
| | Compute conversion to physical units as function of wavelength. |
| Output data: | `LMS_STD_REDUCED_CUBE` |
| | `LMS_STD_BACKGROUND_CUBE` |
| | `LMS_STD_REDUCED_1D` |
| | `LMS_STD_TELLURIC_1D` |
| | `FLUXCAL_TAB` |
| Expected accuracies: | TBD |
| QC1 parameters: | `QC LMS STD STRAYLIGHT MEAN` |

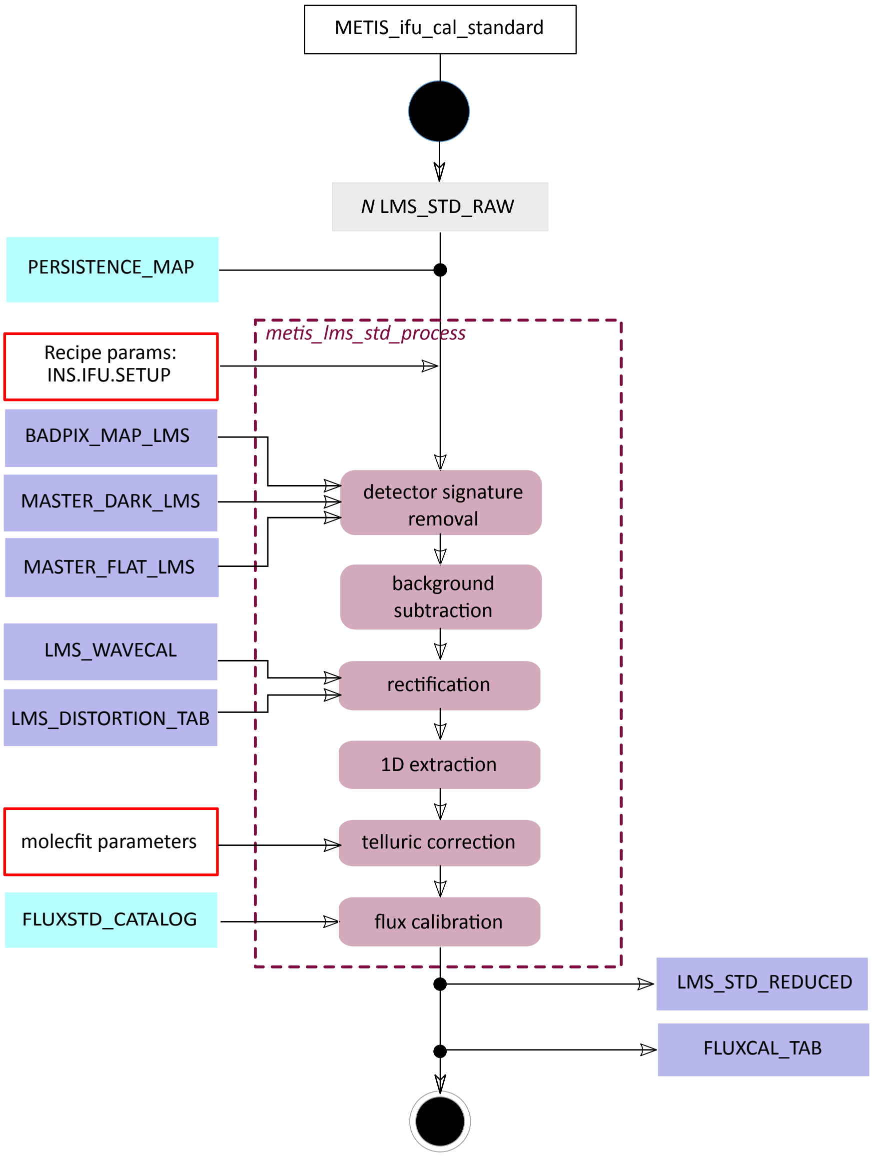



**Figure 27:** `metis_lms_std_process` – reduction of LMS flux standard frames and flux calibration (not all data products are shown).

### 5.5.4 LMS science reduction

This recipe performs basic reduction of raw science exposures applying dark and RSRF correction and flux calibration (i.e. conversion of pixel values to physical units) on each exposure individually. The recipe shall be able to process data from either the nominal or the extended wavelength mode. For the nominal mode, all slices belong to the same echelle order. For the extended mode, slices belonging to the same echelle order are grouped and processing is iterated over the echelle orders.

The level of stray light is estimated in the dark areas between the spectra and subtracted from the entire frame. The distribution of stray light across the field can only be characterised once the instrument is built. It is to be hoped that subtraction of a constant or a low-level 2D polynomial fit will be sufficient.

The sky and thermal background, as well as residual straylight, is estimated from blank sky observations if these are available in the sequence of input frames or by combining (dithered) science frames. The initial wavelength solution is taken from the daylight calibration. It may be checked and corrected by measuring atmospheric lines if a sufficient number is available in the limited wavelength range.

A telluric correction is determined by this recipe by automatically extracting a 1D spectrum from "object" pixels identified by a thresholding algorithm. `molecfit` is applied to this spectrum and the correction is mapped back to the reduced 2D images or 3D cubes using the wavelength images. In an interactive environment (Reflex workflow) the telluric correction may be improved by asking the user to define an extraction aperture adapted to the target structure.

Various levels of output data can be envisaged:

- Reduced 2D detector images. These are accompanied by additional information describing the geometry of the slice layout, target position and wavelength calibration to the extent that the exposure can be combined with other exposures into a single rectified spectral cube. This information can be stored in the FITS header or a table extension.
- A rectified spectral cube for each exposure with a linear wavelength grid, constructed by resampling each spectral slice onto a spatial-wavelength grid common to all slices. The spatial pixels are rectangular with along-slit pixel scale given by the detector pixel scale and the across-slit pixel scale given by the slice width.
- A spectral cube obtained by combining all exposures taken within a template. This step involves the image reconstruction discussed in Sect. 8.9 of [AD1]. Whether this step is included in the present recipe `metis_lms_sci_process` or is postponed to the more general recipe `metis_lms_sci_postprocess` is TBD. It may be formally required to do the image reconstruction here if templates are set up to obtain a fixed set of spatially dithered and rotated exposures aimed at reconstructing a fully sampled PSF in both spatial dimensions.

For the nominal mode, each output is a single-extension FITS file corresponding to one echelle order. For the extended mode, each of the echelle orders results in an extension in a multi-extension FITS file.

The recipe as descibed here is run in the science pipelines. For the observatory pipeline, a variant of the recipe may be implemented with reduced functionality and output. The observatory recipe may also have to include features to determine QC parameters for the LM-band images that are taken in parallel with the LMS exposures, similar to `metis_lm_img_sci_process` (Sect. 5.2).

| | |
|---|---|
| Name: | `metis_lms_sci_process` |
| Purpose: | Reduction of individual science exposures. |
| Requirements: | METIS-6131 |
| Type: | Science |
| Templates: | `METIS_ifu_obs_FixedSkyOffset` |

| | |
|---|---|
| | METIS_ifu_obs_GenericOffset |
| | METIS_ifu_ext_obs_FixedSkyOffset |
| | METIS_ifu_ext_obs_GenericOffset |
| | METIS_ifu_app_obs_GenericOffset |
| | METIS_ifu_clc_obs_FixedSkyOffset |
| | METIS_ifu_vc_obs_FixedSkyOffset |
| | METIS_ifu_ext_app_obs_GenericOffset |
| | METIS_ifu_ext_clc_obs_FixedSkyOffset |
| | METIS_ifu_ext_vc_obs_FixedSkyOffset |
| | METIS_ifu_cal_psf |
| Input data: | Dithered science exposures. |
| | Blank sky images (if available) |
| | Master dark |
| | Master flat (2D relative spectral response function) |
| | Bad pixel mask |
| | Wavelength calibration image |
| | Flux calibration table |
| | Distortion table |
| | Line spread kernel to be used with molecfit |
| Parameters: | telluric correction (yes/no) |
| | more TBD |
| Algorithm: | Subtract dark, divide by master flat |
| | Estimate stray light and subtract |
| | Estimate background from dithered science exposures or blank-sky exposures and subtract. |
| | Apply flux calibration . |
| | Rectify spectra and assemble cube |
| | Extract 1D object spectrum |
| | Compute telluric correction and apply to reduced images and cube |
| Output data: | LMS_SCI_REDUCED (2D, per exposure) |
| | LMS_SCI_REDUCED_TAC (2D, per exposure) |
| | LMS_SCI_BACKGROUND (2D, per exposure) |
| | LMS_SCI_REDUCED_CUBE (3D, per exposure) |
| | LMS_SCI_REDUCED_CUBE_TAC (3D, per exposure) |
| | LMS_SCI_COMBINED (3D) |
| | LMS_SCI_COMBINED_TAC (3D) |
| | LMS_SCI_OBJECT_1D (1D) |
| | LMS_SCI_TELLURIC_1D |
| Expected accuracies: | TBD |
| QC1 parameters: | TBD |

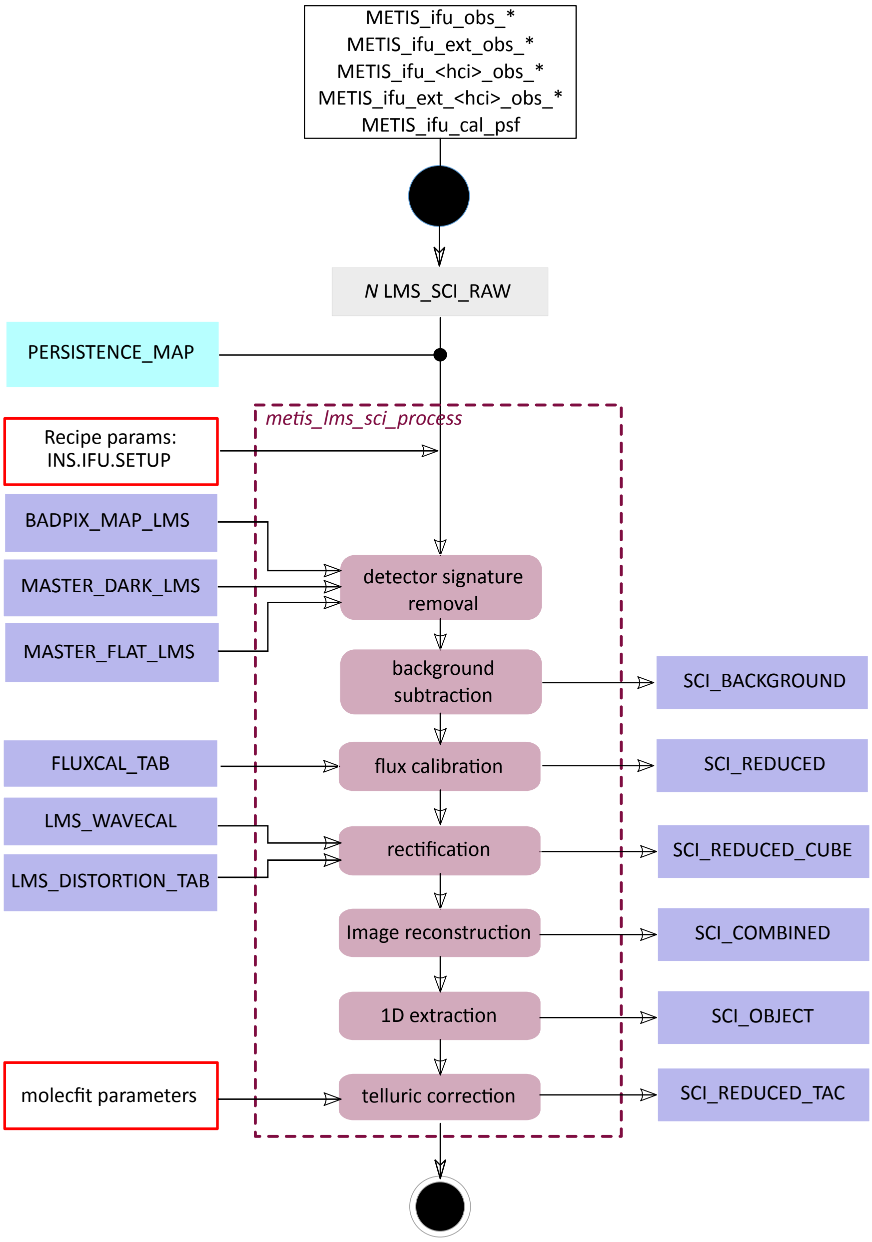



**Figure 28:** metis_lms_sci_process – reduction of LMS science frames.

### 5.5.5 LMS telluric absorption correction

This recipe corrects for telluric absorption in a reduced LMS data cube. The correction is done via a model atmospheric spectrum derived with `molecfit`.

An automatic telluric correction can be performed as part of `metis_lms_sci_process`. In an interactive environment it may be better to do the telluric correction as a separate post-processing step with a user-defined aperture for the extraction of a 1D object spectrum. The spectrum is extracted from a combined cube (`LMS_SCI_COMBINED`) but may be applied to other products of `metis_lms_sci_process` specified in the input set of frames.

| | |
|---|---|
| Name: | `metis_lms_tellcorr` |
| Purpose: | Remove telluric absorption features |
| Requirements: | METIS-6091 |
| Type: | Calibration / post processing |
| Templates: | — |
| Input data: | `LMS_SCI_COMBINED` – reduced combined LMS cube |
| | `LSF_KERNEL` – Line spread kernel to be used with `molecfit` |
| | `ATM_PROFILE` – Atmospheric input profile to be used with `molecfit` |
| Parameters: | extraction aperture parameters |
| | `molecfit` parameters |
| | atmospheric profile incl. radiometer data |
| | line spread kernel |
| Algorithm: | extract 1D spectrum |
| | Application of molecfit |
| Output data: | `LMS_SCI_REDUCED_TAC` |
| Expected accuracies: | TBD |
| QC1 parameters: | TBD |

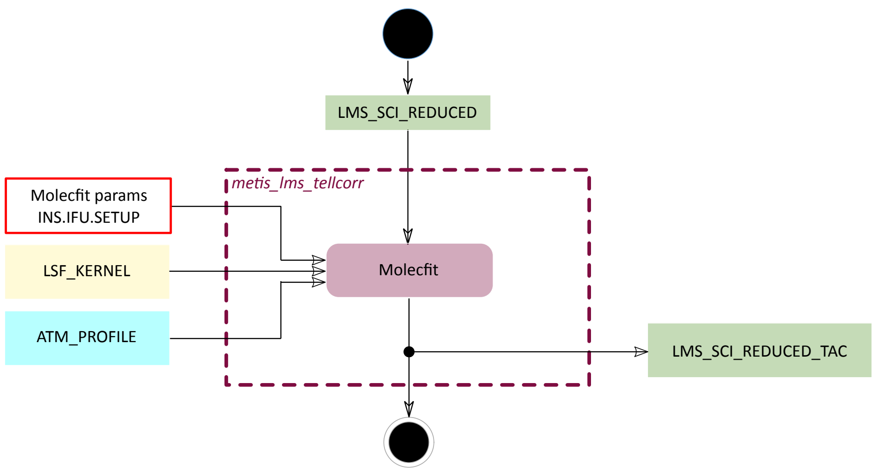



**Figure 29:** `metis_lms_tellcorr` – telluric correction of reduced LMS science cubes.

### 5.5.6 LMS science postprocessing

This recipe combines a number of reduced LMS exposures covering a different spatial and wavelength ranges into a single data cube. The positions and orientations of the exposures may differ as follows:

**Spatial dithering:** The target is placed at different positions along and across the slice. Along-slice dithering aids in background subtraction, across-slice dithering is necessary image reconstruction given that the slice width undersamples the PSF.

**Field rotation:** The field is rotated by 90 degrees between exposures. The cube of a single exposure has different pixel scales along and across the slice. The goal of combining exposures at different rotation angles is to reconstruct images on a square grid with pixel scale given by the detector scale (8.2 mas). The exact procedure remains to be investigated; one of the major challenges is to find the exact centre of rotation (Sect. 8.9 of [AD1]).

**Spectral dithering:** Sequences of exposures are taken at various echelle angles in order to cover an increased contiguous wavelength range. In the extended mode, such a sequence may cover the wavelength gaps between echelle order coverage.

In order to allow coaddition of data from separate OBs, possibly taken months apart, the wavelengths will be corrected to the heliocentric reference system before coaddition.

The recipe is only used in the science-grade pipelines, not at the observatory.

| | |
|---|---|
| Name: | `metis_lms_sci_postprocess` |
| Purpose: | Coaddition and mosaicing of reduced science cubes. |
| Requirements: | METIS-6131 |
| Type: | Science |
| Templates: | — |
| Input data: | Reduced science cubes (`LMS_SCI_REDUCED`, `LMS_SCI_REDUCED_TAC`) |
| Parameters: | TBD |
| Algorithm: | Determine cubic output grid encompassing all input cubes |
| | Resample input cubes to output grid |
| | Coadd |
| Output data: | `LMS_SCI_COADD` |
| | `LMS_SCI_COADD_ERROR` |
| QC1 parameters: | — |

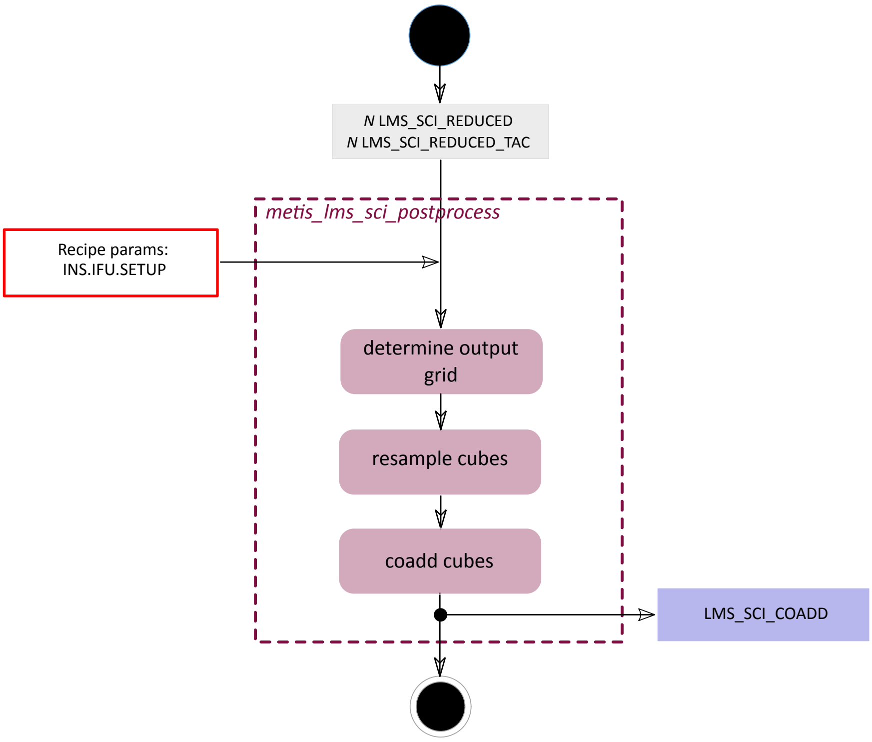



**Figure 30:** `metis_lms_sci_postprocess` – post-processing (coaddition) of reduced LMS science frames.

### 5.5.7 LMS distortion calibration

Calibration of the geometric distortion of the LMS is done by observing a pin hole mask located in a focal plane within the instrument. The distortion is described in terms of a polynomial model whose coefficients can be used to map positions in in the detector array to sky positions. Measurement of the FWHM of the spots gives an indication of the variation of spectral resolution across the field of view.

| | |
|---|---|
| Name: | metis_lms_distortion |
| Purpose: | Determine geometric distortion coefficients for the LMS. |
| Requirements: | METIS-6087, METIS-6073 |
| Type: | Calibration |
| Templates: | METIS_ifu_cal_distortion |
| Input data: | Images of multi-pinhole mask. |
| Parameters: | TBD |
| Algorithm: | Calculate table mapping pixel position to position on sky. |
| Output data: | LMS_DISTORTION_TABLE<br>LMS_DIST_REDUCED |
| Expected accuracies: | TBD |
| QC1 parameters: | QC LMS DISTORT RMS: RMS deviation between measured position and model<br>QC LMS DISTORT FWHM: Measured FWHM of spots<br>QC LMS DISTORT NSPOTS: Number of identified spots |

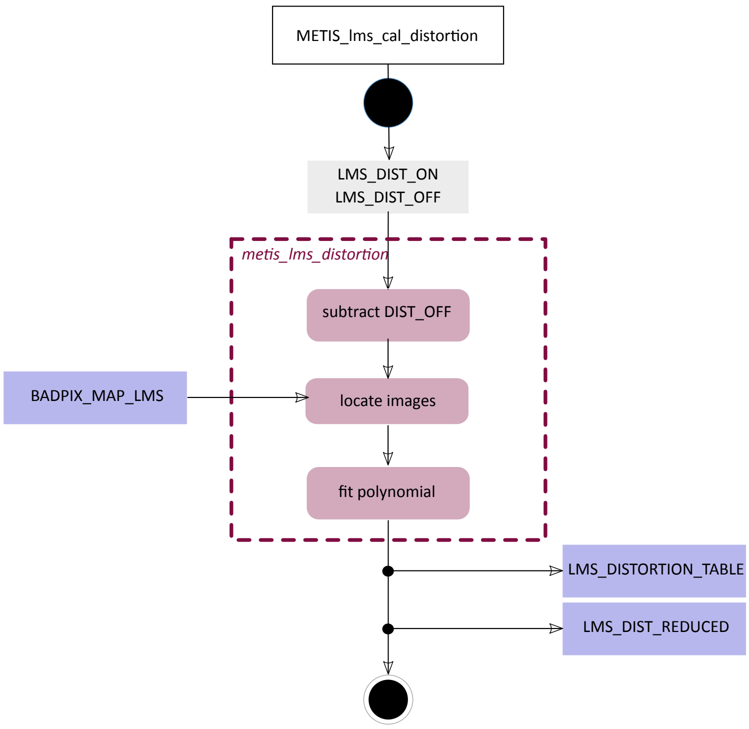



**Figure 31:** metis_lms_distortion – LMS distortion calibration