Spectroscopic Data Systems (SDS):

PEPSI Data Reduction User Manual

Version 1.0 – January 30, 2020

Contents

1 Revision history

Issue	Date	Changes	Responsible
V1.0	22.01.2020	First issue	II

2 About this document

This document outlines Image Processing and Data Analysis Facilities of the Spectroscopic Data Systems (SDS) software package.

3 Introduction

The data reduction pipeline is running on the PEPSI data reduction server and processing all incoming images without user interaction.

In order to start the program, type `sds 2` to open FITS Image Browser, or `sds 1` to open FITS Spectrum Browser (by typing `sds 12` opens them both). The command `sds 3` open FITS Table Browser to operate with FITS Binary Tables.

4 FITS Image Browser

Images in the current directory are all shown in the browser table and any image can be selected with the table bar and displayed by pressing `Enter`.

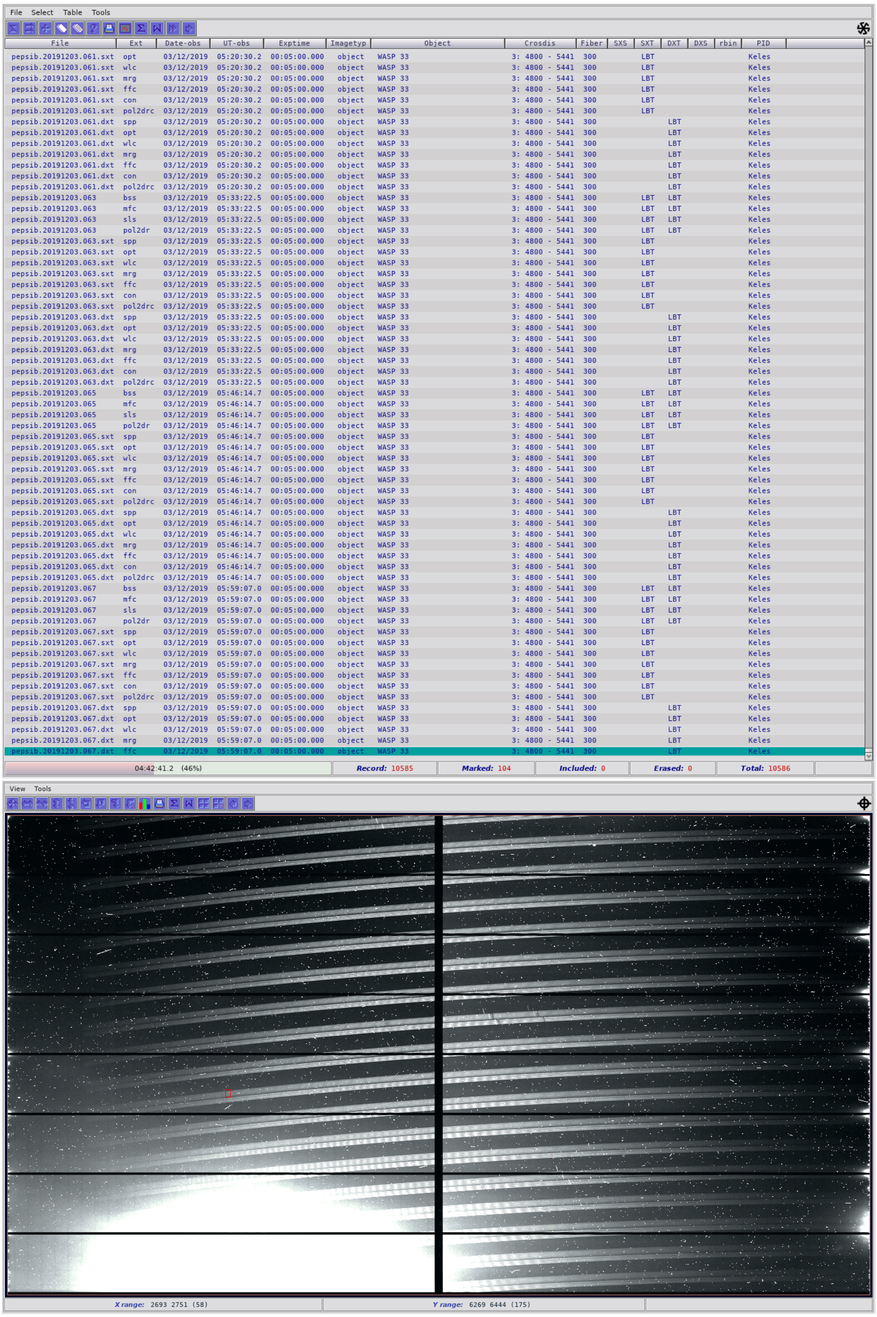
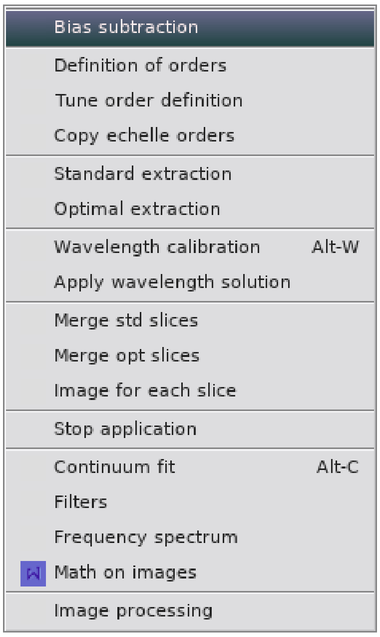


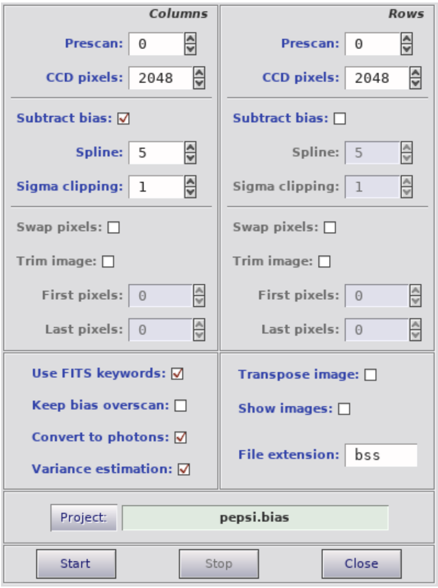
Figure 1: The FITS Image Browser table (left) with the Image Browser Display (right).

4.1 Image Browser Tools Menu



- `Bias subtraction` - in Sec.4.2
- `Definition of orders` uses calibration tracing flat field spectra made for each slice separately to define traces for each order and every slice with a 3D polynomial fit. Creates polynomial fit files with extension `trace`. The échelle order numbers can be assigned with `Alt-F9` from the Image Display located in its `Tools` menu.
- `Tune order definition` fits existing order definition from tracing flats to the selected image (e.g. science or flat field image) to remove any offsets between them.
- `Copy echelle order` copies order definition from tracing flat to any selected image by creating a FITS record `TRACE` with the tracing file name in it (with extension `trace`). In case of PEPSI context it also adds the slicer suffix `SXS`, `SXT`, `DXT`, or `DXS` to the keyword. The tracing flat has to be tagged as `Included` with `Alt-Ins` and the target images tagged as `Marked` with `Ins` keys.
- `Standard extraction` integrates the flux for each slice and all orders without cosmic spices elimination. Creates image with extension `std`.
- `Optimal extraction` integrates the flux for each slice and all orders with cosmic spices elimination by constructing a spatial profile image from the flux distribution in cross-dispersion direction with the subsequent fit to the raw data. Creates resulting image with extension `opt` and `spp` for the spatial profile.
- `Wavelength calibration` - in Sec.4.3
- `Apply wavelength solution` creates a wavelength calibrated image with the wavelength solution taken from the ThAr image. The calibration image has to be tagged as `Included` with `Alt-Ins` and the target images tagged as `Marked` with `Ins` keys.
- `Merge std slices` creates image (`mrg`) with slices merged into a single order with the wavelength scale of the central slice. In this mode the flux and its variances are co-added from the rebinned pixels.
- `Merge opt slices` the same as before but in this mode the flux is averaged with weights as the inverse variance of the rebinned pixels.
- `Image for each slice` creates separate images for each slice separately. The slice number is added to the resulting image name.
- `Stop application` allows to stop some lengthy processing procedures without dialog window, e.g. order definition or optimal extraction.
- `Continuum fit` - in Sec.??
- `Filters` - in Sec.??
- `Frequency spectrum` - in Sec.??
- `Math on images` - in Sec.4.4
- `Image Processing` - in Sec.4.5

4.2 Bias subtraction



The bias subtraction uses the original raw images with extension `fits` and is a part of the Image Processing pipeline. In order to validate bias subtraction settings as well for testing or development purposes it can be opened from `Tools` menu of the Image Browser.

- ☐ `Prescan` and `CCD pixels` defines CCD prescan width and the number of CCD pixels after which the overscan starts: applicable only to a single amplifier CCD device.
- ✓ `Subtract bias` tells whether the bias overscan shall be subtracted in columns and/or rows.
- ☐ `Spline` defines the spline smoothing factor to smooth and subtract overscan.
- ☐ `Sigma clipping` defines the statistical level at which the spikes in the bias overscan are be rejected.
- ✓ `Swap pixels` tells to swap each column or row in the image: applicable only to a single amplifier CCD device.
- ✓ `Trim image` enables skipping the number of columns or rows at the beginning and the end of the image: applicable only to a single amplifier CCD device.
- ✓ `Use FITS keywords` tells to use FITS header `TRIMSEC` keyword to trim the resulting unbiased CCD image.
- ✓ `Keep bias overscan` enables to keep bias overscan in the image after bias subtraction with no image trimming applicable: this is useful for testing and development.
- ✓ `Convert to photons` allows to convert ADUs to photoelectrons according to the CCD gain factor (e/ADU) given in the FITS header. For a single amplifier CCD it uses `GAIN` FITS keyword and for the mosaic CCD it uses indexed `GAIN1`, `GAIN2`... keywords.
- ✓ `Variance estimation` allows to create additional image section in the FITS file where the variances for each pixel are stored. The variance is estimated with the CCD gain factor and the readout noise obtained from the bias overscan. In case the image is not converted to photoelectrons, the variance is estimated in Eds.
- ✓ `Transpose image` tells to swap CCD columns and rows.
- ✓ `Show images` allows to display resulting images as processed.
- ☐ `File extension` specifies the file extension for the resulting image.
- ■ `Project` opens the File Selector window to choose another project file. All parameters of this application can be saved into a specific project file and retrieved any time later.
- ■ `Start` starts processing a single or selected images.
- ■ `Stop` interrupts the processing sequence.
- ■ `Close` closes the dialog window.

Since PEPSI uses a mosaic CCD with 16 amplifiers, the bias subtraction procedure uses `AMPSEC` (image region with prescan and overscan) and `IMASEC` (image region without extra-scans) FITS keywords for each amplifier. The relevant FITS keyword for the PEPSI CCD are shown as follows where the overscan in columns and rows is equal to 50 pixels.

```
EXTEND  =                    T       / Extension is present
MOSAIC  =                    T       / Image is CCD mosaic
DETSIZE = '[1:10560,1:10560]'        / Detector size
DETECTOR= 'STA1600LN'                / STA Archon controller X12-F 1.0.1028

AMPSEC1 = '[1:1370,1:5330]'      / Amplifier index section     AMPSEC9 = '[1:1370,5331:10660]'      / Amplifier index section
IMASEC1 = '[1:1320,1:5280]'      / Image index section         IMASEC9 = '[1:1320,5381:10660]'      / Image index section
AMPSEC2 = '[1371:2740,1:5330]'   / Amplifier index section     AMPSEC10= '[1371:2740,5331:10660]'   / Amplifier index section
IMASEC2 = '[1371:2690,1:5280]'   / Image index section         IMASEC10= '[1371:2690,5381:10660]'   / Image index section
AMPSEC3 = '[2741:4110,1:5330]'   / Amplifier index section     AMPSEC11= '[2741:4110,5331:10660]'   / Amplifier index section
IMASEC3 = '[2741:4060,1:5280]'   / Image index section         IMASEC11= '[2741:4060,5381:10660]'   / Image index section
AMPSEC4 = '[4111:5480,1:5330]'   / Amplifier index section     AMPSEC12= '[4111:5480,5331:10660]'   / Amplifier index section
IMASEC4 = '[4111:5430,1:5280]'   / Image index section         IMASEC12= '[4111:5430,5381:10660]'   / Image index section
AMPSEC5 = '[5481:6850,1:5330]'   / Amplifier index section     AMPSEC13= '[5481:6850,5331:10660]'   / Amplifier index section
IMASEC5 = '[5481:6800,1:5280]'   / Image index section         IMASEC13= '[5481:6800,5381:10660]'   / Image index section
AMPSEC6 = '[6851:8220,1:5330]'   / Amplifier index section     AMPSEC14= '[6851:8220,5331:10660]'   / Amplifier index section
IMASEC6 = '[6851:8170,1:5280]'   / Image index section         IMASEC14= '[6851:8170,5381:10660]'   / Image index section
AMPSEC7 = '[8221:9590,1:5330]'   / Amplifier index section     AMPSEC15= '[8221:9590,5331:10660]'   / Amplifier index section
IMASEC7 = '[8221:9540,1:5280]'   / Image index section         IMASEC15= '[8221:9540,5381:10660]'   / Image index section
AMPSEC8 = '[9591:10960,1:5330]'  / Amplifier index section     AMPSEC16= '[9591:10960,5331:10660]'  / Amplifier index section
IMASEC8 = '[9591:10910,1:5280]'  / Image index section         IMASEC16= '[9591:10910,5381:10660]'  / Image index section
```

The conversion to photoelectrons is done with `GAIN` FITS keywords for each amplifier, but the variance is estimated with the additional gain factor slope `GAINS` which provides the gain factor value at a given ADU number of the pixel. The readout noise measured from overscan of each amplifier is stored into the FITS header of the image and used for variance estimation.

```
GAIN1   =  1.550280   / CCD amplifier gain factor in e/ADU      GAINS1  =  0.662213   / CCD amplifier gain slope times 65535
GAIN2   =  1.553919   / CCD amplifier gain factor in e/ADU      GAINS2  =  0.741984   / CCD amplifier gain slope times 65535
GAIN3   =  1.559687   / CCD amplifier gain factor in e/ADU      GAINS3  =  0.631926   / CCD amplifier gain slope times 65535
GAIN4   =  1.539479   / CCD amplifier gain factor in e/ADU      GAINS4  =  0.700027   / CCD amplifier gain slope times 65535
GAIN5   =  1.562029   / CCD amplifier gain factor in e/ADU      GAINS5  =  0.645251   / CCD amplifier gain slope times 65535
GAIN6   =  1.551208   / CCD amplifier gain factor in e/ADU      GAINS6  =  0.642080   / CCD amplifier gain slope times 65535
GAIN7   =  1.558944   / CCD amplifier gain factor in e/ADU      GAINS7  =  0.657344   / CCD amplifier gain slope times 65535
GAIN8   =  1.552657   / CCD amplifier gain factor in e/ADU      GAINS8  =  0.647146   / CCD amplifier gain slope times 65535
GAIN9   =  1.522927   / CCD amplifier gain factor in e/ADU      GAINS9  =  0.603137   / CCD amplifier gain slope times 65535
GAIN10  =  1.549798   / CCD amplifier gain factor in e/ADU      GAINS10 =  0.615742   / CCD amplifier gain slope times 65535
GAIN11  =  1.550713   / CCD amplifier gain factor in e/ADU      GAINS11 =  0.638433   / CCD amplifier gain slope times 65535
GAIN12  =  1.558488   / CCD amplifier gain factor in e/ADU      GAINS12 =  0.604920   / CCD amplifier gain slope times 65535
GAIN13  =  1.550717   / CCD amplifier gain factor in e/ADU      GAINS13 =  0.625721   / CCD amplifier gain slope times 65535
GAIN14  =  1.551005   / CCD amplifier gain factor in e/ADU      GAINS14 =  0.656871   / CCD amplifier gain slope times 65535
GAIN15  =  1.561832   / CCD amplifier gain factor in e/ADU      GAINS15 =  0.651176   / CCD amplifier gain slope times 65535
GAIN16  =  1.588823   / CCD amplifier gain factor in e/ADU      GAINS16 =  0.637058   / CCD amplifier gain slope times 65535

RON1    =     2.242   / CCD amplifier readout noise in ADU      RON9    =     2.258   / CCD amplifier readout noise in ADU
RON2    =     2.149   / CCD amplifier readout noise in ADU      RON10   =     2.233   / CCD amplifier readout noise in ADU
RON3    =     2.032   / CCD amplifier readout noise in ADU      RON11   =     1.810   / CCD amplifier readout noise in ADU
RON4    =     2.149   / CCD amplifier readout noise in ADU      RON12   =     2.097   / CCD amplifier readout noise in ADU
RON5    =     2.112   / CCD amplifier readout noise in ADU      RON13   =     2.040   / CCD amplifier readout noise in ADU
RON6    =     1.972   / CCD amplifier readout noise in ADU      RON14   =     2.071   / CCD amplifier readout noise in ADU
RON7    =     2.178   / CCD amplifier readout noise in ADU      RON15   =     2.130   / CCD amplifier readout noise in ADU
RON8    =     2.157   / CCD amplifier readout noise in ADU      RON16   =     2.116   / CCD amplifier readout noise in ADU
```

The resulting image with extension `bss` will only retain modified `IMASEC` list of keywords to define the position of each amplifier, which may be used later for some other applications (e.g. CCD gain calibration).

What is not shown in the dialog window but used in the Image Processing pipeline is the use of a master bias or dark image specific for a given CCD device. The master images are part of the calibration sequence and comprise a Windsor sum of a large number of exposures (e.g. 300) to minimize readout noise. For the master bias image the exposure time is zero and for the dark is an hour. The dark master image is then scaled with the exposure time to the bias subtracting image.

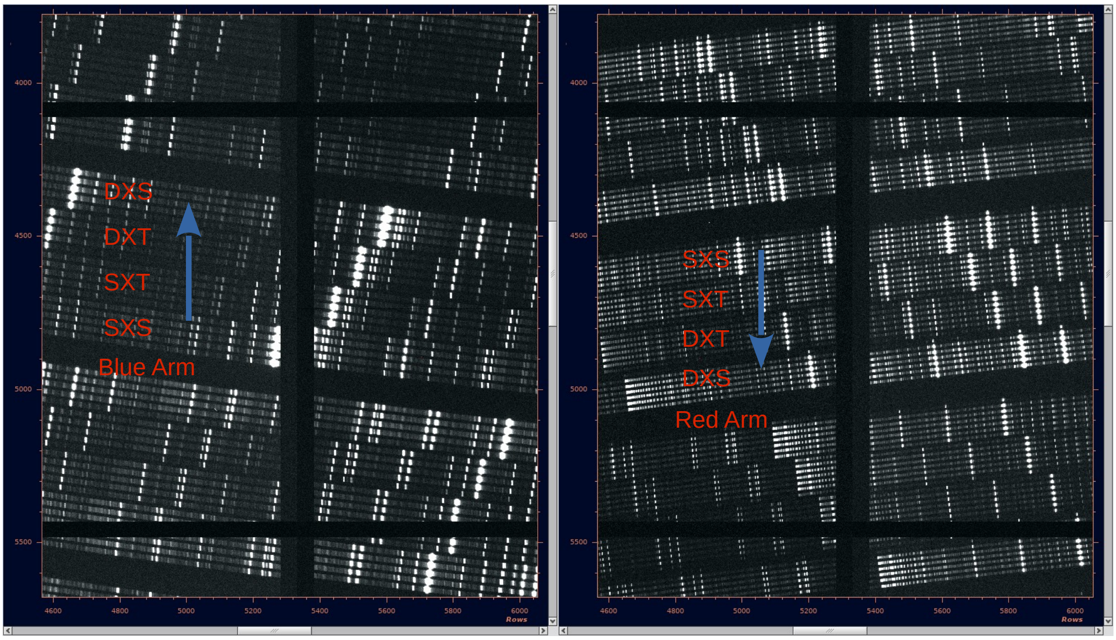


Figure 2: Shown a fragment of the raw ThAr image where overscan areas in CCD columns (horizontal bands) and CCD rows (vertical band) is visible as well as the gap between spectral orders for 200 μm fiber with five image slices. The image origin $(0, 0)$ is on the top left. Shown the location of each image slicer for the left (SX) and right (DX) sides for target (T) and sky (S). The blue arrow shows the direction of échelle orders increase for the blue and red arms.

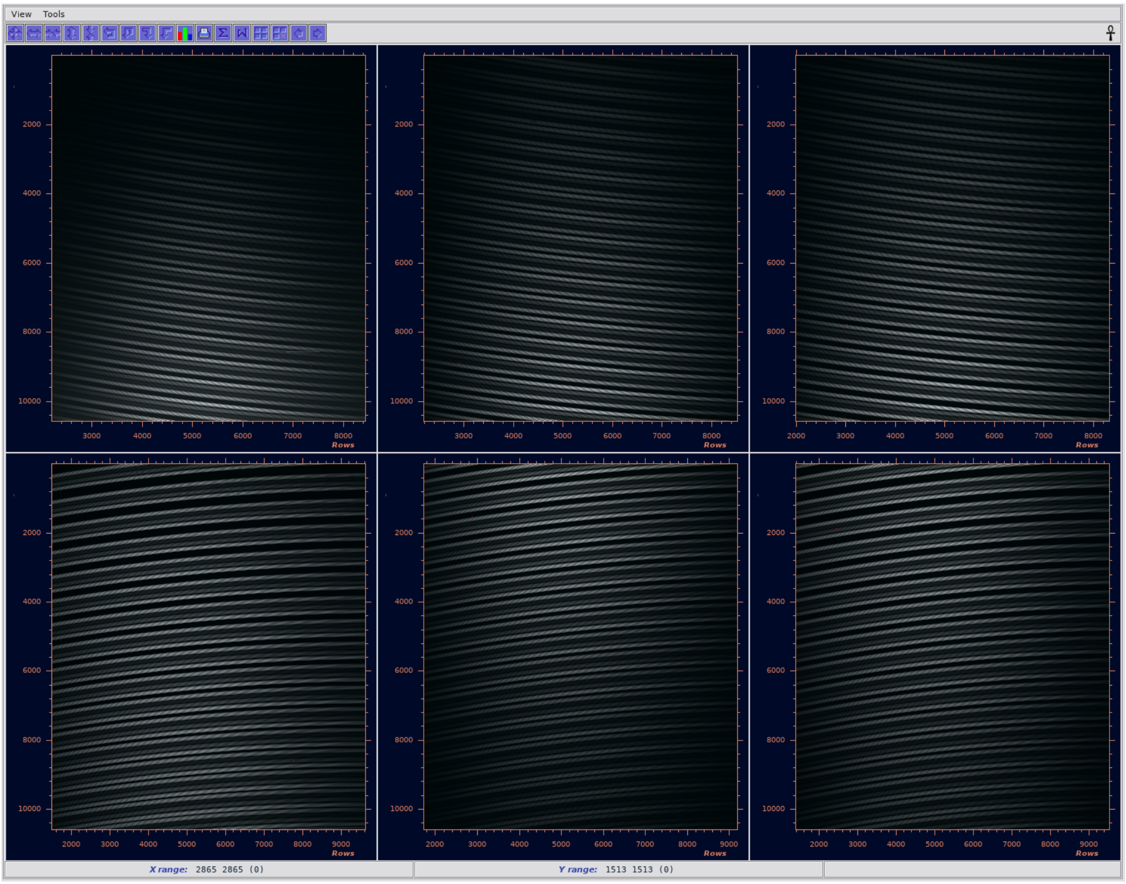


Figure 3: Shown bias subtracted and trimmed master flat fields images for the blue CD123 (top) and the red CD456 (bottom).

4.3 Wavelength calibration

The wavelength calibration is performed on the image of standard extraction (`std`) of the ThAr calibration lamp. The wavelength calibration is part of the Image Processing pipeline which processes the image without user interaction. In order to inspect the quality of the fit or for testing or development purposes it can be opened from `Tools` menu of the Image Browser or by pressing `Alt-W`.

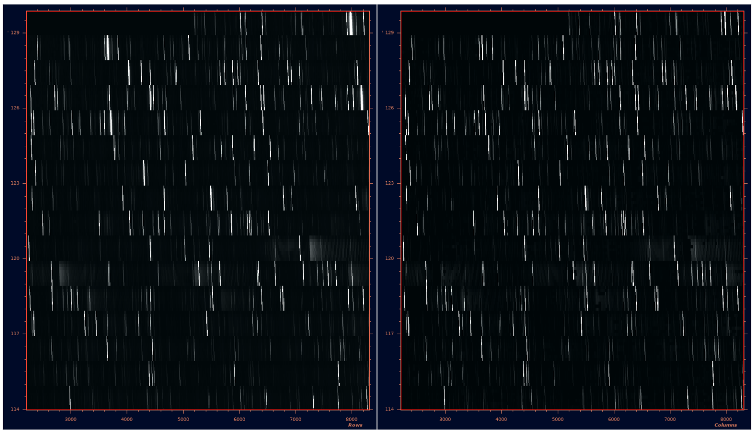


Figure 4: A ThAr standard extraction image with extension `std` for all orders and each slice (here for 130L slicer with nine slices) on the left and the image with extension `gss` for the Gaussian profile lines fit on the right.

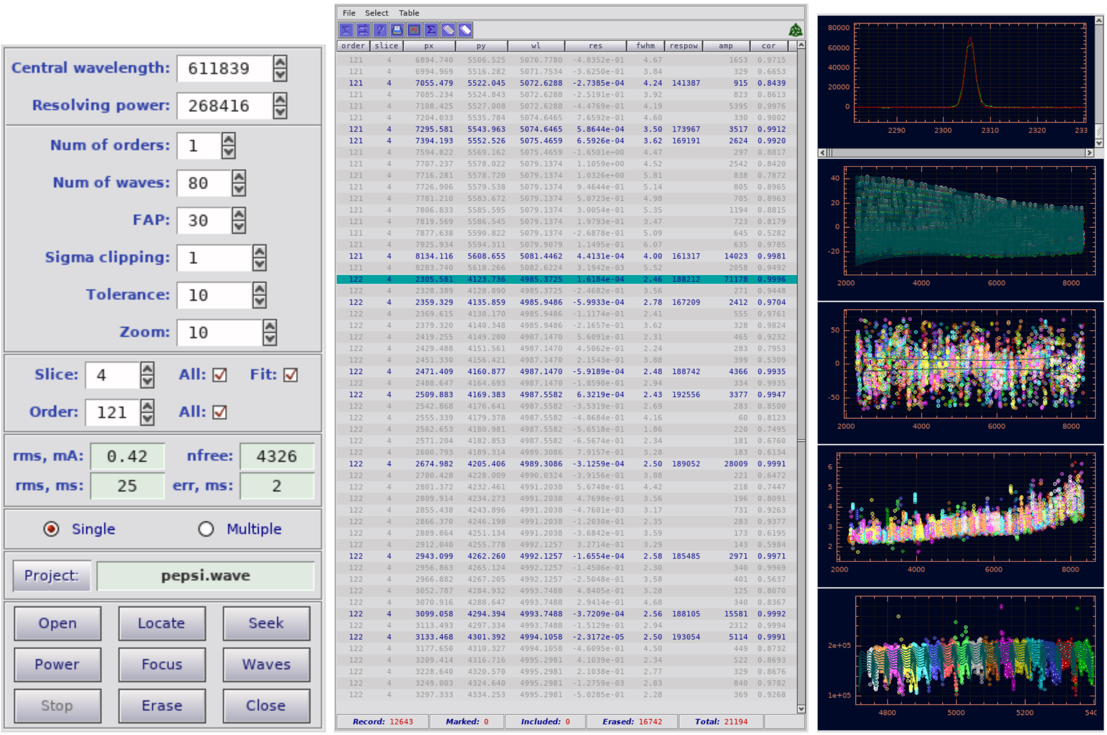


Figure 5: Shown the dialog window (left), the line identification table (middle), and the resulting plots of the wavelength solution (right).

4.3.1 The dialog window

- ☐ `Central wavelength` in Å is the wavelength in the first échelle order in the image center. The value is used as the initial approximation for the wavelength solution and is specific for each spectrograph.

☐ `Resolving power` is used as the initial approximation of the linear dispersion for each order as one half of its inverse value (hence for two CCD pixels). The value is the same for different fibers with various resolving powers and for different CCD binning modes, but specific for each spectrograph

☐ `Num of orders` allows to change the central échelle order number within a range e.g. ± 1 of the number given. This may assume that the central order number for the image center is not exact as it can fall exactly between two orders.

☐ `Num of waves` specifies the swing range in wavelength around the central wavelength. One step is 10 CCD pixels.

☐ `FAP` stands for the False Alarm Probability and used for the 3D polynomial fits to reject insignificant polynomial coefficients. Low FAP retains less significant terms and high FAP retains the most significant terms. The integer FAP parameter here is $-\log 10$ of the probability value.

☐ `Sigma clipping` defines the separation level between statistical and systematical noises in the resistant statistic in order to mask out outlayers of the fit.

☐ `Tolerance` defines the final accepted quality of the fit as the error of the fit in m/s in the image center divided by half of the median FWHM of all line widths, e.g. for an image with two pixels line width FWHM, the tolerance is 10 m/s. This definition makes it invariant for different fibers with various resolving powers (and line widths FWHM) and for different CCD binning modes

☐ `Zoom` is the width as the multiple of the line FWHM to display the original line and its Gaussian fit in the window (upper left) when browsing the line identification table.

☐ `Slice` displays the resulting fit only for a given slice.

☐ `Order` displays the resulting fit only for a given order.

✓ `All` displays the resulting fit for all slices or orders

✓ `Fit` displays polynomial fit curves to the plot panels of the resulting fit (which may be too dense in some cases).

★ The four status boxes show the merit parameters of the fit: rms in mÅ, rms in m/s, number of free parameters, and the error of the fit in the image center in m/s.

◎ `Single` or `Multiple` is to make the wavelength solution for a single image of a number of selected images.

■ `Project` opens the file selector window to select another project file. All parameters of this application can be saved into a specific project file and retrieved any time later.

■ `Open` opens another image from the Image Browser.

■ `Locate` starts to detect all spectral lines in the image for every slice of each order and make a Gaussian fit to them.

■ `Seek` starts to seek the wavelength solution by swinging around the central wavelength and central order. It starts with a fit of the robust polynomial to the trial wavelength table to select good lines for a slice in all orders, then it proceeds with the resistant 2D polynomial fit to all slices and orders in five stages. The successful fits is saved into a binary file with extension `was` and the merits of the fit are stored in the FITS header of the file (as in Sec.4.3.4).

■ `Power` creates separate 1D FITS spectra for each slice in all orders of the 3D robust polynomial fit to the resolving power estimate for all spectral lines used in the wavelength solution. These are used for the spectral synthesis to define the instrumental profile FWHM at a given wavelength and for the quality control.

- `Focus` makes the best focus position for a given slice selected from the series of focusing sequence images for the quality control and is not using or requires the wavelength solution to be made. This auxiliary function makes a 3D robust polynomial fit to FWHM of all lines in the line identification table versus their position in CCD rows, order number, and the focus position of the optical camera. The minimum of the fit for a given CCD row and order number along the focus is the best focus value. The resulting 1D FITS file is saved with extension `focus` for all orders and 50 equally spaced CCD rows.
- `Waves` makes wavelength calibrated image (in wavelength scale, `wlc`) from the ThAr calibration image and slices merged image (`mrg`).
- `Stop` interrupts processing.
- `Erase` removes all items in the line identification table and erases the polynomial fit.
- `Close` closes the dialog window.

4.3.2 The line identification table

The table is stored as the FITS binary table with extension `wat` with its columns described as follows. The lines which are used in the wavelength solution are of the normal state in the Table Browser (i.e. in blue color) and the lines which are rejected to the fit are in erased state (i.e. in light gray color).

`order` - order number of the line.

`slice` - slice number of the line.

`px` - the Gaussian centroid of the line fit in CCD rows.

`py` - position of the line center in CCD columns from the tracing polynomial fit.

`wl` - wavelength of the line after wavelength solution.

`res` - residual of the wavelength fit for a given line in Å which is scaled to the wavelength of the central order.

`fwhm` - line width in pixels.

`respow` - resolving power for the line given its FWHM, wavelength, and the dispersion after the fit.

`amp` - intensity of the line.

`cor` - correlation coefficient of the line defined by the Gaussian profile fit.

4.3.3 The wavelength solution plots

1. The top plot shows the Gaussian profile fit to the line selected in the line identification FITS Table Browser. The width of the plot in CCD rows is controlled by the `Zoom` multiplier to the line FWHM.
2. The wavelength solution fit is the difference in radial velocity (km/s) of the dispersion polynomial of a given order and of the central order of the image. It has a characteristic obtuse trapezoid shape whose orientation depends on the blue or red arm. The horizontal axis is CCD rows.
3. The residuals of the fit in radial velocity (m/s) with the error of the fit polynomial overplotted at 3σ level. The horizontal axis is CCD rows.
4. FWHM plot in pixels versus CCD rows for all lines used in the fit
5. The resolving power estimates for each line used in the fit overplotted with the 3D robust polynomial fit versus wavelength scale.

4.3.4 The wavelength solution merit parameters

The wavelength solution (`WAS`) merit parameters are saved into the FITS header of the ThAr image and also automatically added as columns of the Browser Table.

`WASRMS` - rms in m/s

`WASERR` - fit error in m/s for the image center

`WASTOL` - tolerance for two pixels in m/s

`WASFREE` - degrees of freedom

`WASTIME` - processing elapsed time in sec

`WASREP` - median resolving power of all lines

`WASREQ` - resolving power quartile

`WASFWHM` - median FWHM of spectral lines in pixels

`WASFWHQ` - FWHM quartile in pixels

`CENTRODE` - central échelle order number

`WASCENT` - image center wavelength for the first order at which the wavelength solution was committed

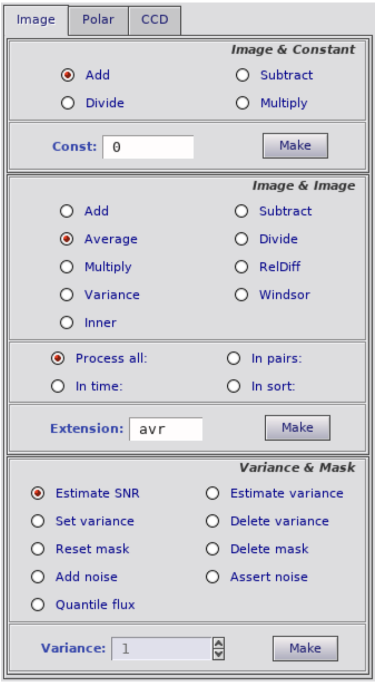
`WASREPO` - resolving power for two pixels at which the wavelength solution was committed

The last two parameters are also propagated along the dependency tree up to the original raw image, so that in case the image has to be re-processed next time it will have a better initial guess parameters.

If the two parameters `WASCENT` and `WASREPO` are not present in the FITS header, the application uses the default parameters from the project file displayed in the dialog window.

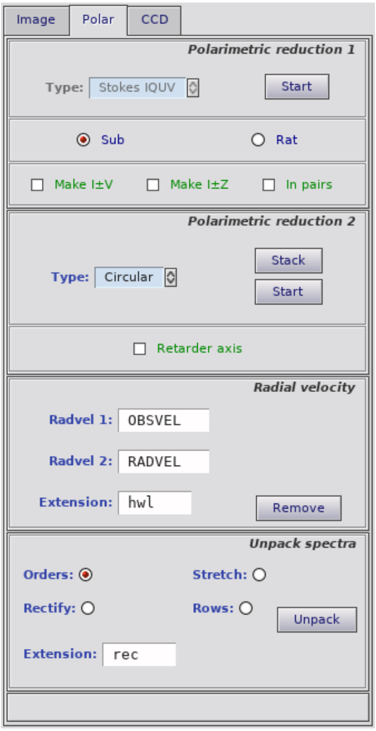
In the case the central order number `CENTRODE` has been changed in the wavelength solution, its new value updates the order definition polynomial fit file (`trace`) and saved into the FITS header of the associated tracing flat image and propagated up along the dependency tree.

4.4 Math on images



- Image & Constant
  - ⊙ `Add`, `Subtract`, `Divide`, `Multiply` selects the function to use.
  - ☐ `Constant` value.
  - ■ `Make` starts operation on a single or selected images. Division and multiplication also changes the variances of the images. The resulting image is saved with the same name.
- Image & Image
  - ⊙ `Add` makes a sum of selected images according to the processing mode.
  - ⊙ `Subtract` subtracts all selected images in pairs or one image (tagged as `Included`) from all selected (tagged as `Marked`).
  - ⊙ `Average` makes a weighted average according to the processing mode.
  - ⊙ `Divide` divides all selected images in pairs or all selected images (tagged as `Marked`) by one image (tagged as `Included`).
  - ⊙ `Multiply` makes a product of all selected images in pairs or all selected images. .
  - ⊙ `RelDiff` makes a relative difference of all selected images in pairs.
  - ⊙ `Variance` makes the variability image of all selected images.
  - ⊙ `Windsor` makes the Windsor (trimmed) sum of all selected images (by ignoring the five lowest and five highest values in each pixel).
  - ⊙ `Inner` makes the inner region of all selected images by selecting the innermost part of these images for testing purposes.
  - ⊙ `Process all` allows to process all selected images tagged as `Marked` (with `Ins`). The common image tagged as `Included` (with `Alt-Ins`) is used in the `Subtract` mode as the image to be subtracted and in the `Divide` mode as the denominator image.
  - ⊙ `In pairs` allows to process all selected images tagged as `Marked` (with `Ins`) in pairs.
  - ⊙ `In time` allows to process all selected images tagged as `Marked` (with `Ins`) which are exposured on the same date.
  - ⊙ `In sort` allows to process all selected images tagged as `Marked` (with `Ins`) according to the sorting criteria, e.g. if sorted by fiber and cross-disperser it will process all images separately with the same combination of the fiber and cross-disperser. It opens the table sort window to make the sorting combination.
  - ☐ `Extension` for the resulting image.
  - ■ `Make` starts selected sequence.
- Variance & Mask
  - ⊙ `Estimate SNR` processes all selected images and estimates 75% quantile of the signal/noise for all pixels given their intensity and variance. Has sense only for extracted images.
  - ⊙ `Estimate variance` processes all selected images and estimates their variances according to Photon statistics with the use of `GAIN` FITS keyword (CCD gain factor e/ADU) and `RON` as the readout noise in ADUs.
  - ⊙ `Set variance` to a constant value given in the edit window.
  - ⊙ `Delete variance` removes image section with the variance matrix.
  - ⊙ `Reset mask` changes the image mask values to its normal state.

- ⊚ `Delete mask` removes image section with the mask matrix.
- ⊚ `Add noise` adds normal noise to each pixel intensity with the variance specified in the edit window.
- ⊚ `Assert noise` replaces each pixel intensity with a mean value averaged in a window with its size specified in the edit window. This is useful for signal/noise estimation of flat field images. Saves the resulting image with extension `snr`.
- ⊚ `Quantile flux` makes a random selection of image pixels and takes the difference between 5% quantiles of the intensities (i.e. 5% smallest and 5% largest). Writes the result into FITS keyword `FLUX`.



- Polarimetric reduction 1
  - ■ `Type` specifies the expected type of Stokes vector derived.
  - ⊚ `Sub` derives Stokes parameters with the difference method
  - ⊚ `Rat` derives Stokes parameters with the ratio method
  - ✓ `Make` $I \pm V$ produces additional images where $I + V$ and $I - V$ are calculated.
  - ✓ `Make` $I \pm Z$ produces additional images where $I + Z$ and $I - Z$ are calculated, where Z is the null profile.
  - ✓ `In pairs` processes images in pairs for the two polarization angles.
  - ■ `Start` processes selected images to derive Stokes $IQUV$ parameters and creates separate images for each Stokes parameter with extensions `i`, `q`, `u`, `v`, and `z`.
- Polarimetric reduction 2
  - ■ `Type` specifies the expected type of Stokes vector derived.
  - ✓ `Retarder axis` specifies the type of the fit.
  - ■ `Stack` processes selected images to combine them versus polarization optics angle.
  - ■ `Start` makes a global linear least-squares fit of the polarization modulation function versus angle of the retarder to the data. In case the `Retarder axis` is included, it performs a non-linear least-squares fit with the retarder axis versus wavelength as a free parameter.

4.5 Image Processing

This menu command opens Image Processing window to start the pipeline manually for e.g. development and testing. The pipeline can be restarted from any point of the Image Processing up to the end. It can take all available images to process or a number of selected images, as well as specific slices (fibers) or cross-dispersers (CD) can be selected.

- `Bias subtraction`: it uses bias overscan to remove bias offset and trim the image according to the `TRIMSEC` keyword in the FITS header. Then it uses available master bias or dark CCD image to remove any structure in the bias level. The ADU values in the image are transformed to photoelectrons according to the `GAIN` factor for each amplifier given in the FITS header and the photon noise is estimated taking into account the slope of the gain factor with ADUs. All these parameters are introduced to the FITS header by the Archon CCD readout software (which is part of the PEPSI control program). Creates image with extension `bss`.

- `Master flat image correction` remove CCD pixel-to-pixel noise with the use of a master flat field image which comprises a sum of 300 exposures of the de-focused flat field. The master flat image is not normalized to the blaze function, hence, the processed image will have essentially blaze function removed after division. All science and calibration images are divided by the master flat. Creates image with extension `mfc`.

- `Scattered light subtraction` removes any residual flux between spectral orders by using a 2D spline fit with resistant statistics to avoid spectral orders from the fit. Creates image with extension `sls`.

- `Order definition` uses special calibration tracing flat field spectra made for each slice separately to define traces for each order and every slice with a 3D polynomial fit. It uses the FITS keyword `CENTRODE` to define the échelle order number in the image center for each CD and the direction of its increase. This parameter is introduced by the PEPSI control program. Creates polynomial fit files with extension `trace`.

- `Standard extraction of orders` applies to the wavelength calibration images with ThAr lamp or Fabry-Perot etalon (FPE). It takes the nearest in time order definition file and uses it for integration of the flux for every order and all slices in each CCD row. It results in the image with the flux integrated for each slice and all orders. Creates image with extension `std`.

- `Wavelength calibration` makes the wavelength solution of the extracted ThAr image: first it locates all emission spectral lines and searching for the best fit with the given approximate wavelength in the first order in the image center and the expected resolving power for two pixels (to define the dispersion). Creates several files associated with the wavelength solution having extension `was` and `wat`, and the image of the Gaussian fit to the ThAr lines with extension `gss`.

- `Optimal extraction of orders` integrates the flux of the science exposure image and its cosmic spikes elimination by constructing spatial profile for each order and every slice. Once it is smoother with a spline it is linearly fitted to the raw data for each CCD row. It results in the image with the flux integrated for each slice and all orders. Creates images with extension `opt` and `spp`.

- `Wavelength calibration` applies the wavelength solution of the associated ThAr image to the optimally extracted image by adding wavelength grid for every slice in all order for each CCD row. It proceeds with merging slices in wavelength scale of the central slice into one spectrum for each spectral order. Creates image with extension `wlc` and `mrg`.

- `Master flat spectrum correction` make the division of the master flat field spectrum which reduced the same way as the science échelle image. This removes any optical fringes and other features common to both images. Creates image with extension `ffc`.

- `Continuum normalization` make a low degree 2D polynomial fit to the continuum level of the normalized image by using a resistant statistics to avoid spectral lines from the fit. It proceeds with the constrained least-squares solution to fit the overlapping in wavelength parts of adjacent spectral orders to each other. Creates image with extension `con`.

- `Rectification of spectra` creates an 1D spectrum out of the normalized image by averaging overlapping parts of the spectral order with their weights as the inverse variance in each pixel. The wavelength scale is preserved for each spectral order. Creates spectrum with extension `rec`.
- `Continue` proceeds with the image processing interrupted as some point. The pipeline starts to resolve all dependencies, i.e. checking that the intermediate files for a given science image exist in every step of image processing. In case the file does not exist, it proceeds at that point for a given science image.

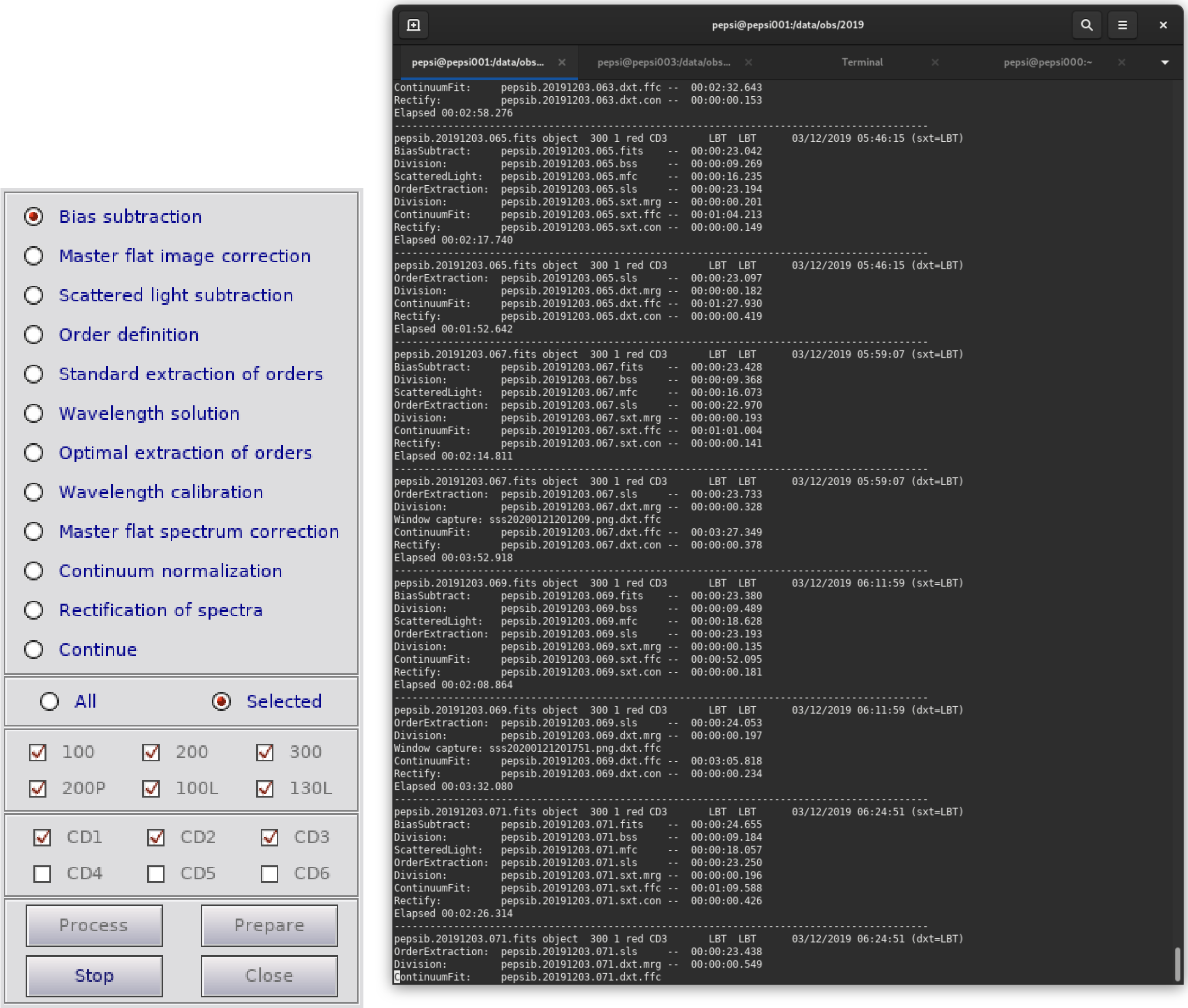


Figure 6: The Image Processing dialog window which stars the reduction pipeline (left). A typical Image Processing printout on a terminal shows the steps involved and the time spent (right).

◎ `All` instructs the pipeline that all science images in the current working directory are to be processed depending on the selection of the check-boxes for the slicers (fibers) and cross-dispersers.

◎ `Selected` instructs the pipeline that only selected science images are to be processed (with extension `fits`).

✓ `100 200 300 200P 100L 130L` all or some image slicers can be selected.

✓ `CD1 CD2 CD3 CD4 CD5 CD6` all or some cross-dispersers can be selected

■ `Process` starts image processing from a given step and selection criteria.

- `Prepare` starts processing only calibration images in the working directory and can be used prior to the processing of the science images.
- `Stop` interrupts image processing at any step. To resume the process use `Continue` radio-box in the reduction steps.
- `Close` closes the image processing window.

4.5.1 Image dependency tree

The Image Processing pipeline creates a number of intermediate files which are used at different stages of the processing. They define the dependencies of the processing flow which means that if the file with a certain extension is absent, the pipeline with continue processing the image at that step.

`fits` - the original raw image.

`bss` - bias subtracted image.

`mfc` - image after master flat field image correction.

`sls` - scattered light subtracted image.

`trace` - an internal binary file with the order definition fit.

`std` - standard extraction image.

`was` - an internal binary file with the wavelength solution fit.

`wat` - an internal FITS binary table where the wavelength solution lines and their positions are stored.

`gss` - image where the Gaussian fit profiles are stored for wavelength calibration.

`opt` - optimally extracted image.

`spp` - spatial profile image for optimal extraction.

`wlc` - wavelength calibrated image.

`mrg` - image with the slices merged into one order.

`ffc` - image after master flat field spectrum correction.

`con` - normalized image after 2D continuum fit.

`rec` - the resulting 1D spectrum after orders rectification.

`pol2dc`, `pol2dr`, `pol2drc` - polynomial fit images produced at various stages of image processing.

An internal binary file means that it will not appear in the FITS Image Browser. All other regular images will be added to the Browser Table and can be displayed and inspected in the Browser Imager.