



# EUROPEAN SOUTHERN OBSERVATORY

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral

Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

## VERY LARGE TELESCOPE

### VIMOS Pipeline User Manual

VLT-MAN-ESO-19500-3355

Issue 4.0

Date 2008-06-06

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### Change record

Issue/Rev.	Date	Section/Parag. affected	Reason/Initiation/Documents/Remarks
1.0	09/07/2004	All	First version
2.0	30/09/2005	All	Second version
3.0	30/01/2007	All	Third version
4.0	06/06/2008	All	Fourth version

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# 1 Introduction

## 1.1 Purpose

This manual is a complete description of the data reduction recipes used by the the VIMOS pipeline, reflecting the status of the VIMOS pipeline as of June 6, 2008 (version 2.1.11).

The VIMOS pipeline is a subsystem of the *VLT Data Flow System* (DFS). Its target user is ESO *Data Flow Operations* (DFO) in the generation of master calibration data, in the reduction of scientific exposures, and in the data quality control. It should also serve as a quick look tool for *Paranal Science Operations* (PSO). Additionally, the VIMOS pipeline recipes are made public to the user community, to allow a more personalised processing of the data from the instrument.

The VIMOS instrument and the different types of VIMOS raw frames are briefly described in Sections 4 and 6, while the usage of the available reduction recipes is presented in Section 5.

More detailed descriptions of the data reduction algorithms used by the individual pipeline recipes can be found in Sections 8 and 9.

In Section 3.1 an overview of what's new on VIMOS Pipeline release 2.1.11 is given.

In Appendix A provides a list of used abbreviations and acronyms.

## 1.2 Acknowledgements

The software package on which the VIMOS pipeline is based was in large parts developed by the VIRMOS Consortium, and it is still the foundation of the current VIMOS imaging and MOS pipelines.

Valuable suggestions on the IFU data reduction pipeline were provided by Eric Emsellem and Arlette Rousset-Pecontal (Centre de Recherche Astronomique de Lyon), and by Martin Roth (Astrophysikalisches Institut Potsdam). Further improvements were later provided by Dr Peter M. Weilbacher (Astrophysikalisches Institut Potsdam), and Dr Katrina Exter (Space Telescope Science Institute).

The feedback we received in numerous discussions with our “beta-testers”, Paola Popesso (ESO Office of the Director General), Piero Rosati and Martino Romaniello (ESO Data Management and Operations Division), Markus Kissler-Patig (ESO Instrumentation Division), and Harald Kuntschner (ST-ECF), was very much appreciated.

Useful advice has been received especially from Sandro D’Odorico (ESO Instrumentation Division) and Stefano Cristiani (INAF – Osservatorio Astronomico di Trieste).

Gianni Marconi, Stephane Brilliant, and Stefano Bagnulo (ESO Paranal Observatory) have been unvaluable for the good collaboration and the constant support in the first VIMOS years.

In particular we want to thank Paola Sartoretti (ESO, Data Management and operations Division), who was a continuous source of useful ideas for improving the pipeline recipes, and for their extensive testing, and Burkhard Wolff who continued her good job.

### 1.3 Reference documents

- [1] VLT Data Flow System Operations Model for VLT/VLTI Instrumentation  
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VLT-SPE-ESO-19600-1233
- [3] Data Flow for VLT instruments Requirement Specification  
VLT-SPE-ESO-19000-1618
- [4] DFS Pipeline & Quality Control – User Manual  
VLT-MAN-ESO-19500-1619
- [5] ESO DICB – Data Interface Control Document  
GEN-SPE-ESO-00000-0794
- [6] Common Pipeline Library User Manual  
VLT-MAN-ESO-19500-2720
- [7] Gasgano User’s Manual  
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## 2 Overview

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

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

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

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

The products of the pipeline are standard FITS files for the master calibration and science products. In addition the pipeline generates data files (PAF and QC files) for the purpose of operational quality control within the observatory.

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

The process of data classification and association is known as data organisation.

An instrument pipeline consists of a set of data processing modules that can be called from different host application, either from the command line with *Esorex*, from the automatic data management tools available at Paranal, or from the graphical *Gasgano* tool.

*Gasgano* is a data management tool that simplifies the data organisation process, offering automatic data classification and making the data association easier (*even if automatic association of frames is not yet provided*). *Gasgano* determines the classification of a file by applying an instrument specific rule, while users must provide this information to the recipes when they are executed manually using *Esorex* from the command line.

In addition, *Gasgano* allows the user to execute directly the pipeline recipes on a set of selected files. An illustrated introduction to *Gasgano* is provided in the "Quick Start" Section of this manual (see page 21).

### 3 What's new

#### 3.1 What's new on release 2.1.11

The following major improvements have been realised on the VIMOS Pipeline since release 2.0:

- Added support for gcc compiler 4.0 or later (release 2.0.14).
- Included a fix to recipe *vmimflatsky*, that incorrectly combined imaging sky flat field frames for any method different from *Average* (release 2.0.15).
- Added support for spectral data obtained with the new red holographic grisms (release 2.1.6).
- Provided a new set of fiber identification tables (IFU\_IDENT) valid for more recent IFU data (release 2.1.6).
- IFU spectral extraction has been improved, thanks to useful discussions with Dr Katrina Exter (Space Telescope Science Institute), both by using a more realistic spatial profile model (keeping into account the differences between fibers) and by improving the optimal extraction algorithm (present release).
- The alignment of the spectral tracing derived from the flat field exposure to the actual scientific exposure has been greatly improved, thanks to a contribution by Dr Peter M. Weilbacher, Astrophysikalisches Institut Potsdam (present release).
- Now the alignment of the arc lamp based wavelength calibration to the position of the observed sky lines can be performed individually for each fiber spectrum, a further contribution by Dr Peter M. Weilbacher.

#### 3.2 What was new on release 2.0

The following major improvements have been realised on the VIMOS Pipeline:

- The wavelength calibration for MOS spectra is now more robust, and accurate calibrations can be obtained even in the case of masks with a narrow distribution of slits (as those used for the observations of spectrophotometric standard stars). A new “blind” arc line identification method has been implemented, based on pattern recognition, that doesn't make use of the first-guess IDS models associated to the input calibration lamps. This option would simplify the reduction of those observations where the initial first-guess models appear to be too far from the real distortions. In addition to that, it is now possible to iterate in a simple way the obtained spectral distortions models, using them as increasingly accurate first-guesses. See Sections 7.14 and 9.7 for further details.
- The reduction of spectra from curved slits is now supported.
- Sky fringing can now be subtracted from the reduced frames obtained from a jittered sequence of exposures, both in MOS and in imaging mode. In MOS mode two different methods have been implemented for this purpose. See Sections 7.12, 7.16, 9.22, and 9.26, for further details.

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- More methods for the stacking of jittered MOS spectra have been made available. See Section 7.16 for further details.
- A new recipe, *vmmoscombine*, is now available for stacking spectra from different nights. See Section 7.17 for further details.
- MOS and IFU spectra, reduced with the recipes *vmifuscience*, *vmmosobsstare* and *vmmosobsjitter*, can now be flux calibrated using the spectro-photometric table produced by the recipe *vmifustandard*, and the new recipe *vmmosstandard*. Another recipe, *vmsspphot*, can be used to apply a flux calibration to already reduced spectra. See the corresponding sections for further details.
- In recipes *vmmosobsstare* and *vmmosobsjitter* the enforced specification of a CCD table, even when bad pixel correction was not requested, has been eliminated.
- An incorrect computation of the RMS of the residuals in IFU fiber tracing and wavelength calibration has been eliminated. This had no effect on the data reduction products, but just on the evaluation of the error of local distortion models fits, while the overall RMS associated to the wavelength calibration was computed correctly. To fix this, one should square-root the RMS values listed in the extraction mask and IDS tables produced with the earliest pipeline release (see tables 7.19.4 and 7.19.5, page 122).
- In the optimal extraction of spectra obtained from the stacking of a jittered sequence of MOS exposures, the computation of the variance didn't keep into account the number of stacked frames. This had the effect of reducing the efficiency of cosmic rays hits rejection. On the other side, this had no effect on the optimal extraction in itself, since modifying consistently the optimal weights by a constant factor doesn't change the final result. Now this problem has been fixed.
- The 1D-extracted sky is a new product of the recipes *vmmosobsstare* and *vmmosobsjitter*.
- The recipe *vmifucombine* now combines IFU reconstructed images of the field-of-view from different quadrants keeping into account the different reference levels used in the relative transmission correction in each quadrant. This is just cosmetics, and it doesn't affect in any way other results from the data reduction process.
- It is now possible to examine the intermediate products of the data reduction steps of the recipe *vmmosobsjitter*. See Section 7.16 for further details.
- The total IFU standard star spectrum is now just summed over the fibers that are really affected by the standard star flux, eliminating severe background contamination, particularly in the case of multiplexed low resolution observations.

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## 4 The VIMOS instrument

VIMOS has been developed under ESO contract by the VIRMOS Consortium, headed by the Laboratoire d'Astrophysique de Marseille.

The instrument has been made available to the community and started operations in Paranal on April 1<sup>st</sup>, 2003.

In this chapter a brief description of the VIMOS instrument is given. A more complete documentation can be found in the VIMOS User Manual, downloadable from <http://www.eso.org/instruments/vimos/>

### 4.1 Overview

VIMOS is aimed at survey-type programs with emphasis on large object samples rather than individual objects. VIMOS is designed for Wide Field Imaging (14' x 16') and extremely high Multi Object Spectroscopy capability (up to several hundred slits). In addition, it has a unique *Integral Field Unit* (IFU) providing a field-of-view up to 1 arc minute at 0.67"/fibre in low resolution spectroscopy.

The field-of-view is split in four identical channels. Field lenses provide a corrected telescope focal plane where flat masks are inserted in MOS mode. For the IFU instrument mode a special mask bearing the IFU pseudo-slits is used. Pupil relay lenses, folding mirrors and collimators direct the light to the four cameras. Grisms are inserted in front of the cameras in spectroscopic mode. The detectors are four 2k x 4k EEV CCDs with pixel size 15  $\mu$  (see <http://www.eso.org/projects/odt/Vimos/vimos.html> for detector design and performance reports of the four VIMOS CCD systems).

### 4.2 Direct imaging

The field-of-view consists of 4 quadrants of 7' x 8' each separated by a cross 2' wide, with a sampling of 0.205"/pixel.

The available filters, U, B, V, R, I, and z, are close to the Mould definition, and allow to minimise the colour terms to transform to the Johnson system.

The filter transmission curves are available from <http://www.eso.org/instruments/vimos>.

### 4.3 Multi-Object-Spectroscopy (MOS)

The multi-object mode of VIMOS uses grisms and masks. ESO distributes the *VIMOS Mask Preparation Software* (VMMPS), a package developed by the VIRMOS Consortium for slit definition and positioning on a preliminary exposure on the sky region to be observed. The user can define rectangular, curved or inclined slits of widths larger than 0.4". The masks are laser cut in INVAR plates on Paranal with the *Mask Manufacturing Unit* (MMU). The instrument cabinet has a capacity of 15 masks, some of which are meant for maintenance and calibration purposes.<sup>1</sup>

There are 6 grisms available, all operating in first order. Their spectral characteristics are given in Table 4.3.1.

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<sup>1</sup>For technical reasons only 7 slots of the masks cabinet are currently used.



Grism	Filter	$\lambda_c$ (Å)	$\lambda$ range (Å)	R	Dispersion (Å/pixel)
LR_red	OS_red	7500	5500 - 9500	210 - 260	7.3
LR_blue	OS_blue	4800	3700 - 6700	180 - 220	5.3
MR	GG475	7000	4800 - 10000	580 - 720	2.5
MR	OS_red	7000	5500 - 9700	580 - 720	2.5
HR_red	GG475	7400	6500 - 8650	2500 - 3100	0.6
HR_orange	GG435	6310	5150 - 7600	2150 - 2650	0.6
HR_blue	none	5100	4100 - 6300	2050 - 2550	0.5

Table 4.3.1: *VIMOS* grisms.  $\lambda_c$  is the zero deviation (or central) wavelength, and  $R$  is the spectral resolution for a 1" MOS slit, corresponding to  $\sim 0.8$  IFU fibre. The spectral ranges are given with the specified filter in. A new set of four holographic HR\_red grisms has been installed in VIMOS on October 5, 2005. Compared to the previous set, the efficiency has increased of about 50%. Before that date, there was no HR\_red grism in quadrant 4 (HR\_orange was used instead). The transmission curves for the four grism/filter units are available at <http://www.eso.org/instruments/vimos>.

With LR grisms, a spectrum will typically span less than 600 pixels along the dispersion direction. This allows a multiplexing factor of 5, *i.e.*, to stack up to five spectra along the dispersion direction, provided that there are enough well spaced targets in the field-of-view.

With MR grisms, a spectrum will span about 2000 pixels when used with the GG475 filter. It is therefore possible to stack up to 2 spectra along the dispersion direction, provided that the slits are positioned at the very edges of the imaging field-of-view.

With HR grisms the spectra extend beyond the detector length, therefore multiplexing is impossible and the observable spectral interval depends on the position of a slit on the mask, spanning about 2400 Å for the HR\_red and HR\_orange grisms, and about 2000 Å for the HR\_blue grism.

A further constraint on the slit positions comes from the presence of the  $0^{th}$ ,  $-1^{st}$  and  $2^{nd}$  grism diffraction orders. At low spectral resolution, a dim second order spectrum at twice the spectral resolution would be included in the CCD in the case of slits located in the lower (*i.e.*, bluer) regions of the mask. This spectrum would likely contaminate the multiplexed first order spectra on the red side of the CCD. Similarly, a mirrored  $-1^{st}$  order spectrum at the same resolution of the  $1^{st}$  order spectrum and with about 1/6 of its luminosity, would be included in the CCD in the case of slits from the highest (*i.e.*, redder) regions of the mask. This spectrum would likely contaminate the multiplexed first order spectra on the blue side of the CCD (see an illustration of  $-1^{st}$  contamination on page 107). For this reason multiplexed slits are constrained to be identical, and to have the same position along the cross-dispersion direction: in the assumption of negligible spectral curvatures in all orders, the  $0^{th}$ ,  $2^{nd}$  and  $-1^{st}$  contaminations would then be removed by the sky subtraction procedure.

Aside from the above considerations, the number of slits that can be accommodated in one mask obviously depends on the target density. Simulations on real fields using VMMPs show that above a density of about  $7 \cdot 10^4/\text{degree}^2$  it is possible to define masks with up to 160 10" long slits/quadrant. This number drops to 125 slits/quadrant at a density of about  $4 \cdot 10^4/\text{degree}^2$ .

## 4.4 Integral Field Unit (IFU)

The VIMOS IFU is the largest ever made for such an application. It consists of 6400 (80 x 80) fibres, coupled to microlenses. The field-of-view is square, with a continuous spatial sampling (the dead space between fibres is below 10% of the fibre-to-fibre distance). At the entrance of the IFU there is a focal elongator providing two spatial samplings of 0.33"/fibre and 0.67"/fibre.

The fibres are split into 16 bundles of 400 fibres each. Each instrument quadrant receives 4 bundles that are arranged along 4 parallel pseudo-slits providing 4 multiplexed series of 400 spectra each.

The field-of-view is modified according to the used spectral resolution. At low spectral resolution the field is respectively 54" x 54" with 0.67"/fibre, and 27" x 27" with 0.33"/fibre, 80 fibres on a side. All the pseudo-slits are illuminated, and the multiplexed spectra belonging to different pseudo-slits would contaminate each other in some measure. For instance, the second order spectra of a bright object on pseudo-slit 2 of quadrant 2 would contaminate the spectra on pseudo-slits 3 and 4, creating obvious ghosts in the corresponding regions of the reconstructed field-of-view (see Figures 4.5.2 and 4.5.3, pages 19–20).

At medium and high resolution just the 4 central bundles on the IFU head are illuminated (see Figure 4.5.3, page 20). Only one pseudo-slit per quadrant is used, since the spectra span the whole detector and multiplexing is impossible. The field-of-view is therefore 4 times smaller, *i.e.*, 27" x 27" with 0.67"/fibre, and 13" x 13" with 0.33"/fibre, 40 fibres on a side.

The fibre-to-fibre distance at detector level is about 5.0 pixels, while the fibre profile FWHM is about 3.2 pixels. The spectral resolution is approximately 1.25 times the spectral resolution corresponding to a 1" slit in MOS mode (see Table 4.3.1). The spectral coverage is identical to the MOS case for LR and MR grisms. For HR grisms the situation is different because the spectral range is too large to be contained on the CCD, and since the central slit-of-fibres is shifted by about 140 pixels from the chip centre in (spectrally) opposite directions depending on the instrument quadrant, the common spectral range is reduced by about 160 Å leading to Table 4.4.1.

Grism	$\lambda$ range (Å)
HR_red	6350 - 8600
HR_orange	5250 - 7550
HR_blue	4200 - 6150

Table 4.4.1: *VIMOS IFU usable spectral range in high spectral resolution mode.*

## 4.5 IFU components numbering scheme

The conventions used in the VIMOS IFU pipeline recipes to indicate IFU fibers, IFU masks and pseudo-slits are described in this section.

**IFU masks:** VIMOS has 4 IFU masks. They are counted as the VIMOS quadrants to which they correspond, *i.e.*, counterclockwise, with the same convention used in the cartesian plane (see Figure 4.5.1).

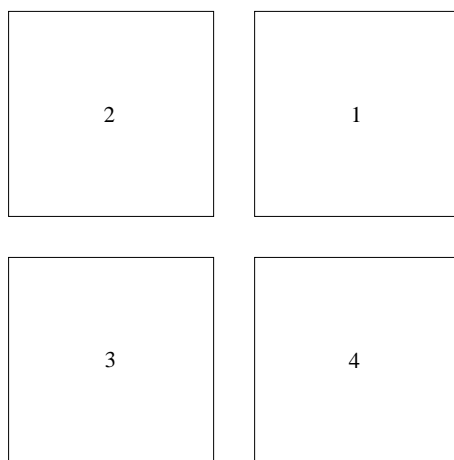


Figure 4.5.1: *Counting VIMOS quadrants.*

In spectral mode, blue is down and red is up in all quadrants.

**IFU pseudo-slits:** Each VIMOS mask hosts 4 IFU pseudo-slits, numbered from 1 to 4. The pseudo-slit 1 is the one that is somewhat more separated from the other ones (see Figure 4.5.2).

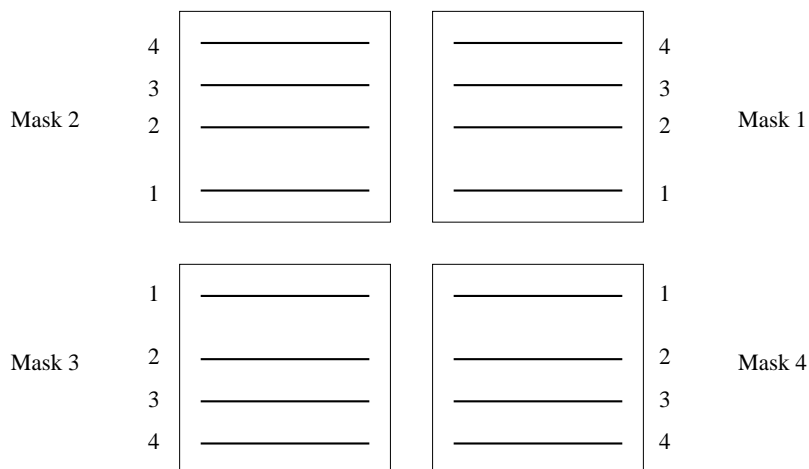


Figure 4.5.2: *Counting IFU pseudo-slits.*

**IFU fibers:** Each IFU pseudo-slit hosts 400 fibers, divided into 5 blocks of 80 fibers each. The fibers are counted from 1 to 400, always starting from the left.

**IFU head:** Each pseudo-slit corresponds to a 20x20 region of the 80x80 IFU head (see Figure 4.5.3).

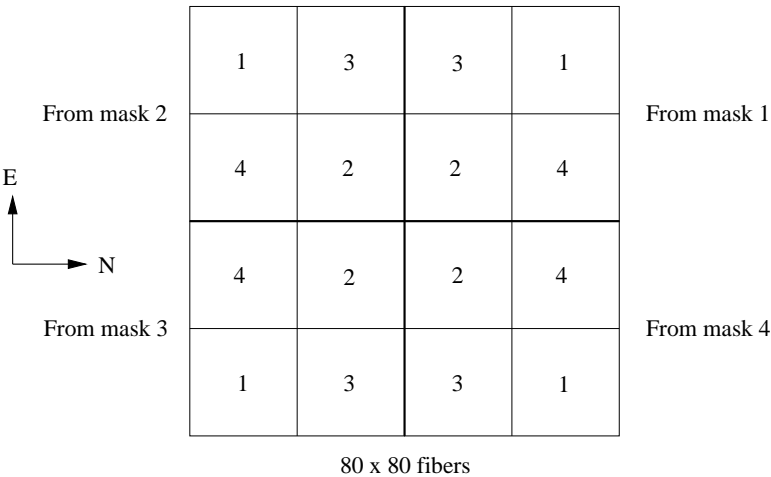


Figure 4.5.3: *IFU head. The number of the corresponding pseudo-slit is indicated within each 20x20 fiber module.*

North is to the right, and East is up. The exact spatial position for each individual fiber is listed in the IFU tables (see Table 7.19.3, page 122).

**Illuminated pseudo-slits:** In LR observations all the pseudo-slits are illuminated (multiplexing). In MR and HR observations, just the central pseudo-slits (numbered 2) are used.

## 5 Quick start

In this section the most immediate usage of the VIMOS pipeline recipes is described. In particular, typical data reduction sessions for each instrument operating mode are presented in Sections 5.3, 5.4, and 5.5.

### 5.1 VIMOS pipeline recipes

The current VIMOS pipeline is based on a set of 23 stand-alone recipes, assigned to different fundamental operations:

Creation of general calibration data:

**vmidet:** creating a bad pixel table, and determining CCD gain and read-out-noise from a sequence of flat fields at different exposure levels.

**vmbias:** creating a master bias from a sequence of raw bias frames.

**vmdark:** creating a master dark from a sequence of raw dark frames.

Creation of direct imaging calibration data:

**vmimflatscreen:** creating a master screen flat field from a sequence of screen flat field frames.

**vmimflatsky:** creating a master sky flat field from a sequence of sky flat field frames.

**vmmasktoccd:** computing transformation between mask and CCD coordinates from an exposure with a pinhole mask.

**vmkyccd:** computing the distortions of the Sky to CCD transformation from an exposure on a field of astrometric stars.

Direct imaging flux calibration:

**vmimstandard:** reducing a photometric standard stars field image, and determining the frame magnitude zeropoint.

**vmimcalphot:** determining the mean zeropoint and, optionally, the extinction coefficient and the colour term from any number of star match tables produced by the *vmimstandard* recipe.

Direct imaging data reduction:

**vmimpreimaging:** reducing a preimaging exposure for the preparation of a MOS mask.

**vmimobsstare:** reducing a science exposure.

**vmimobsjitter:** reducing a stack of jittered science exposures.

Creation of MOS calibration data:

**vmfpflat:** producing a spectral master flat field.

**vmfpcaldisp:** computing the optical distortion, the spatial curvature, and the inverse dispersion models.

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**vmmosstandard:** computing the instrument spectral efficiency and response curves from a standard star exposure.

MOS data reduction:

**vmmosobsstare:** reducing a science exposure.

**vmmosobsjitter:** reducing a stack of jittered science exposures.

**vmmoscombine:** combining a stack of reduced and 2D-extracted slit spectra obtained from different observations.

**vmsspphot:** applying flux calibration to already reduced spectra (this recipe is applicable also to IFU data).

Creation of IFU calibration data:

**vmifucalib:** producing an extraction mask, a wavelength calibration, and a fiber-to-fiber relative transmission correction.

**vmifustandard:** extracting the total standard star spectrum, and computing the instrument spectral efficiency and response curves from a standard star exposure.

IFU data reduction:

**vmifuscience:** reducing a science exposure.

**vmsspphot:** applying flux calibration to already reduced spectra (this recipe is applicable also to MOS data).

**vmifucombine:** compose an image of the field-of-view.

In the next sections a general description on the use of recipes is given, together with more detailed information on the individual recipes.

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## 5.2 Launching pipeline recipes

ESO offers two front-end applications for launching pipeline recipes, *Gasgano* [7] and *EsoRex*, both included in the pipeline distribution. These applications can also be downloaded separately from

<http://www.eso.org/gasgano>  
<http://www.eso.org/cpl/esorex.html>

### 5.2.1 Using Gasgano

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

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

```
gasgano &
```

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

The data are hierarchically organised as preferred by the user. In this example the default grouping is shown, and for clarity only the sub-groups belonging to the first VIMOS quadrant are expanded. After each file name are shown the observation date, the target name, the used grism-filter combination and, as an important reference, an identifier of the type of data, listed in the *CLASSIFICATION* field.<sup>2</sup>

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

Frames can be selected from the main window for being processed by the appropriate recipe: on Figure 5.2.2, the flat field and arc lamp exposures, an already produced master bias frame, and the necessary static calibration tables, are all selected and sent to the *vmifucalib* recipe. This will open a *Gasgano* recipe execution window (see Figure 5.2.3), having all the specified files listed in its *Input Frames* panel.

Help about the recipe may be obtained from the *Help* menu. Before launching the recipe, its configuration may be opportunely modified on the *Parameters* panel (on top). The window contents might be saved for later use by selecting the *Save Current Settings* entry from the *File* menu, as shown in figure.

At this point the recipe can be launched by pressing the *Execute* button. Messages from the running recipe will appear on the *Log Messages* panel at bottom, and in case of successful completion the products will be listed on the *Output Frames* panel, where they can be easily viewed and located back on the *Gasgano* main window.

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

<sup>2</sup>This is known as the data *DO* category, see Section 6, page 41.

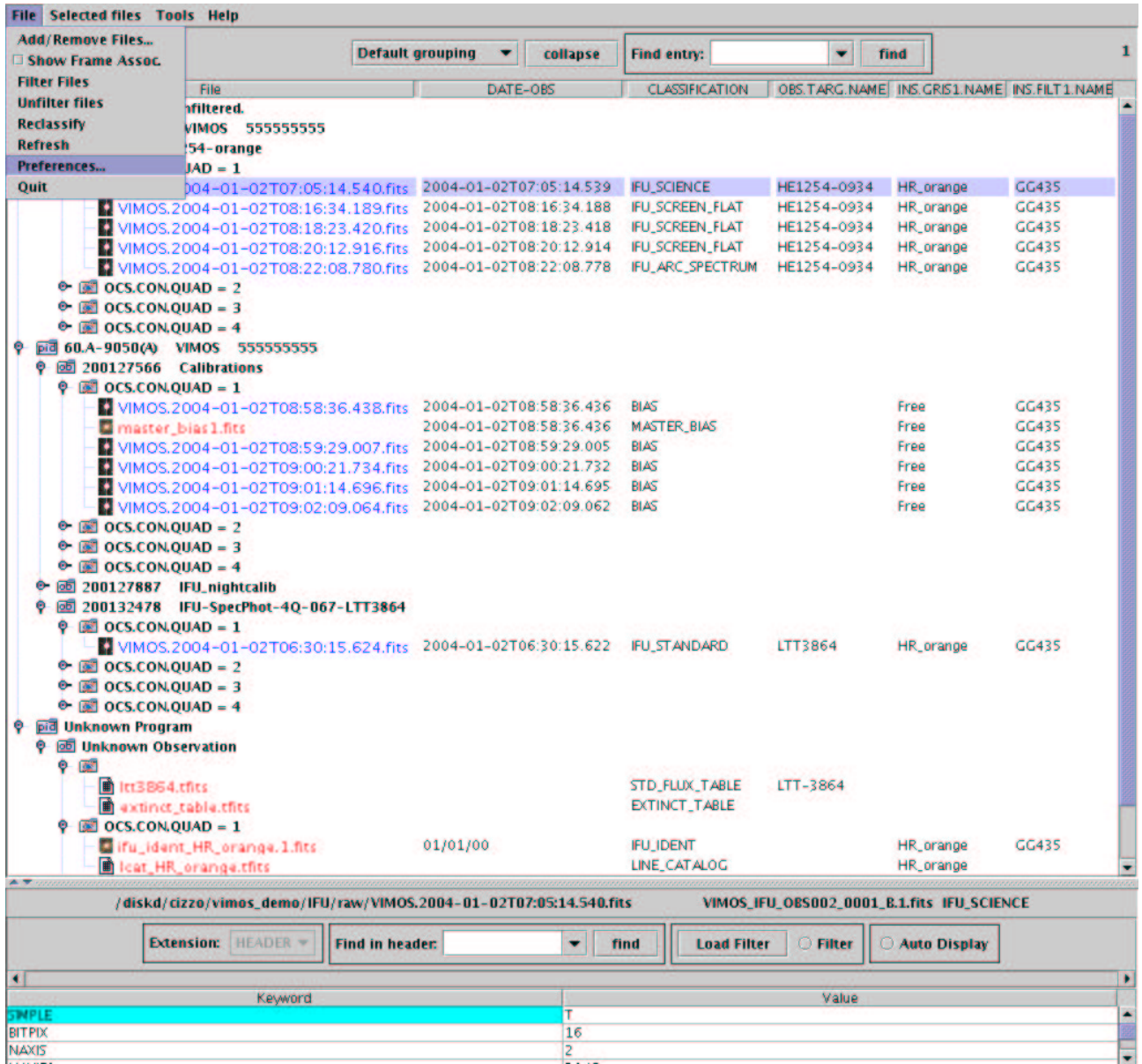


Figure 5.2.1: The Gasgano main window.



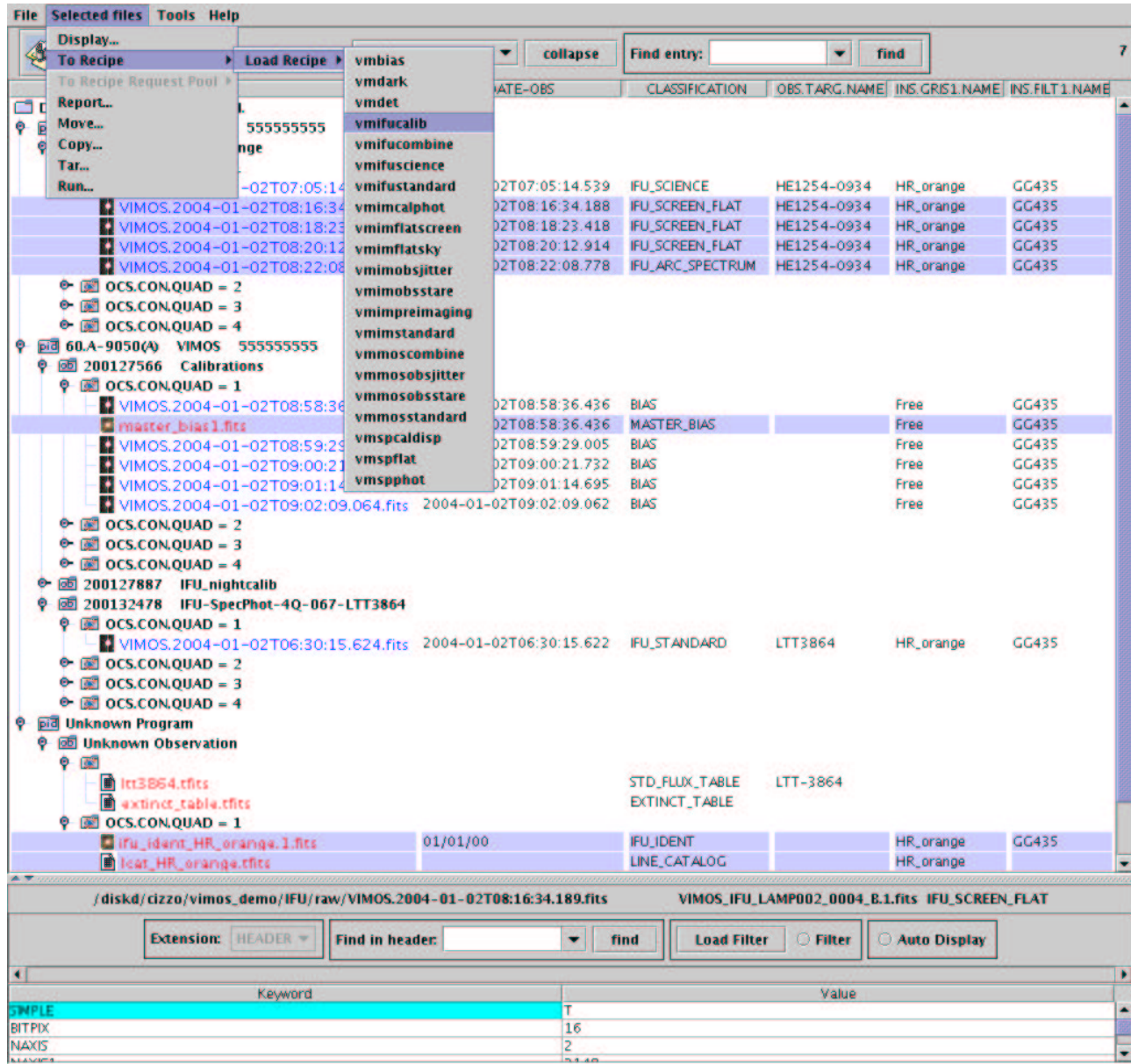


Figure 5.2.2: *Selecting files to be processed by a VIMOS pipeline recipe.*

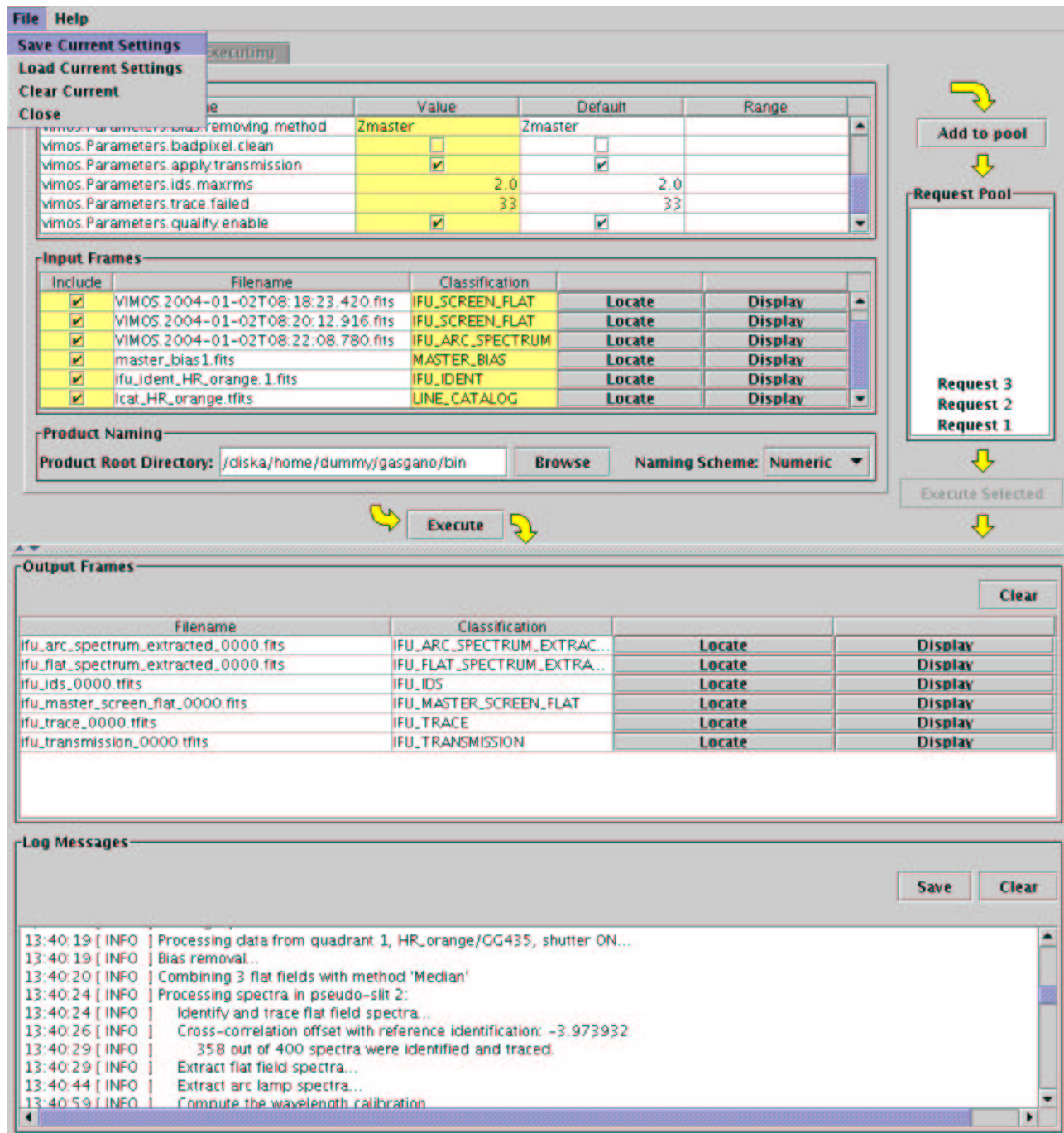


Figure 5.2.3: The Gasgano recipe execution window.

### 5.2.2 Using EsoRex

*EsoRex* is a command line utility for running pipeline recipes. It may be embedded by users into data reduction scripts for the automation of processing tasks. On the other side, *EsoRex* doesn't offer all the facilities available with *Gasgano*, and the user must classify and associate the data using the information contained in the FITS header keywords (see Section 6, page 41). The user should also take care of defining the input set-of-frames and the appropriate configuration parameters for each recipe run:

**The set-of-frames:** Each pipeline recipe is run on a set of input FITS data files. When using *EsoRex* the filenames must be listed together with their DO category in an ASCII file, the *set-of-frames* (SOF), that is required when launching a recipe.<sup>3</sup>

Here is an example of SOF for *EsoRex*, valid for the *vmspcaldisp* recipe:

```
VIMOS.2003-02-04T16:31:53.040.fits  MOS_ARC_SPECTRUM
/home/vimos/cal/mbias.3.fits          MASTER_BIAS
/home/vimos/cal/lcat_LR_red.3.tfits  LINE_CATALOG
/home/vimos/cal/grs_LR_red.3.tfits  GRISM_TABLE
```

The pipeline recipe will access the listed files when required by the reduction algorithm.

Note that the VIMOS pipeline recipes do not proof in any way the correctness of the classification tags specified by the user in the SOF. In the above example, the recipe *vmspcaldisp* will treat the frame `VIMOS.2003-02...` as a `MOS_ARC_SPECTRUM`, the frame `mbias.3.fits` as a `MASTER_BIAS`, etc., even when they do not contain this type of data. The recipe will also assume that all frames are associated correctly, *i.e.*, that they all come from the same instrument quadrant, using the same filter, grism, etc., and that the appropriate calibration files have been specified.

The reason of this lack of control is that the VIMOS recipes are just the DRS component of the complete pipeline running on Paranal, where the task of data classification and association is carried out by separate applications. Moreover, using *Gasgano* as an interface to the pipeline recipes will always ensure a correct classification of all the data frames, assigning the appropriate DO category to each one of them (see Section 5.2.1, page 23).

A recipe handling an incorrect SOF may stop with not immediately understandable error messages at best. In the worst cases, the recipe would apparently run without any problem, producing results that may look reasonable while they are instead flawed.

**Recipe configuration:** Each pipeline recipe may be assigned an *EsoRex* configuration file, containing the default values of the parameters related to that recipe.<sup>4</sup> The configuration files are normally generated in the directory `$HOME/.esorex` (as will be shown in the subsequent examples), and have the same name as the recipe to which they are related, with the filename extension `.rc`. For instance, the recipe *vmbias* has its *EsoRex* generated configuration file named `vmbias.rc`.

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

<sup>3</sup>The set-of-frames corresponds to the *Input Frames* panel of the *Gasgano* recipe execution window (see Figure 5.2.3, page 26).

<sup>4</sup>The *EsoRex* recipe configuration file corresponds to the *Parameters* panel of the *Gasgano* recipe execution window (see Figure 5.2.3, page 26).

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```
# --StackMethod
# Stacking method ( Average | Median | MinMax | Ksigma | Auto )
vimos.Parameters.stacking.method=Average
```

In this example, the parameter `stacking.method` is set to the value `Average`. In the configuration file generated by *EsoRex*, one or more comment lines are added containing information about the possible values of the parameter, and an alias (`StackMethod`) that could be used as a command line option (see subsequent examples).

The hierarchy introduced in the parameter names has currently no effect. Although it is not used at the moment, it is envisaged that this feature will be used in future releases to avoid potential name clashes. The shorter parameter aliases are made available for use on the command line.

The parameter names belonging to the recipe specific configuration files are described in the corresponding recipe sections.

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

The basic format for using *EsoRex* is as follows:

```
esorex [esorex_options] recipe_name [recipe_options] set_of_frames
```

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

```
esorex --recipes
```

To get help for an individual recipe (in the subsequent examples, *vmbias* is used), the following is used:

```
esorex --help vmbias
```

In order to display the current parameters setting of a recipe, the following command may be used:

```
esorex --params vmbias
```

If the default recipe configuration file is not found, or a particular value is not configured within this file, then the system defaults will be shown and used. The command:

```
esorex --create-config vmbias
```

will create in the `$HOME/.esorex` directory a configuration file `vmbias.rc` with the default parameters settings for the recipe *vmbias*. This file can then be modified with the preferred text editor.<sup>5</sup>

A recipe can be run by specifying its name to *EsoRex*, together with the name of a set-of-frames. For instance, the following command line would be used to run the recipe *vmbias* for processing the files specified in the set-of-frames `vmbias.sof`:

---

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

```
esorex vmbias vmbias.sof
```

The recipe parameters can be modified either by editing directly the used configuration file, or by specifying new parameter values on the command line using the command line options defined for this purpose. Such command line options should be inserted after the recipe name and before the SOF name, and they will supersede the system defaults and/or the configuration file settings. For instance, to set the *vmbias* recipe *StackMethod* parameter to *Median*, the following should be typed:

```
esorex vmbias --StackMethod=Median vmbias.sof
```

There are also parameters used to configure the *EsoRex* launcher, that may be listed in an *esorex.rc* configuration file located under `$HOME/.esorex`. On the command line, the *EsoRex* options must be inserted before, and not after, the specified recipe name. The *EsoRex* options are those that are recipe independent, as for instance the verbosity level, the directory where the recipe products should be written, or the permission to overwrite old products with new ones.

Here are some more examples of running a recipe:

```
esorex --output-prefix=test vmmasktoccd --CleanCosmics=true test.sof
esorex --msg-level=debug vmskyccd --SExtractor.Window=1,1,1900,2300 skyccd
esorex vmspflat --ComputeQC=false --FlatMethod=Median in.sof
esorex --time=true vmspcaldisp --CleanBadPixel=false input1.sof
```

In the *vmmasktoccd* example the cosmic ray cleaning is switched on, and the prefix *test\_* is prepended to output products names. The input SOF is the file *test.sof*.

In the *vmskyccd* example the verbosity level is set to *debug*, so that all messages are displayed, including the debug ones. In addition to that, SExtractor operations are restricted to the specified image region. The input SOF is a file named *skyccd*.

In the *vmspflat* example the computation of quality control parameters is turned off, and the flat field trend removal (used in the flat field normalisation) is performed using a median filter. The input SOF is *in.sof*.

Finally, in the *vmspcaldisp* example the execution of the recipe is timed and bad pixels cleaning is turned off. The input SOF is *input1.sof*.

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

### 5.3 Example of imaging data reduction using EsoRex

A simple, typical imaging data reduction procedure using *ESOREX* is described here.<sup>6</sup> It is assumed that the following data are available:

One scientific exposure:

```
VIMOS.2004-09-25T09:27:15.336.fits      IMG_SCIENCE
```

One standard star field exposure:

```
VIMOS.2004-09-25T08:20:10.006.fits      IMG_STANDARD
```

Five bias exposures:

```
VIMOS.2004-09-25T08:00:27.821.fits      BIAS
VIMOS.2004-09-25T08:01:05.604.fits      BIAS
VIMOS.2004-09-25T08:01:44.091.fits      BIAS
VIMOS.2004-09-25T08:02:22.070.fits      BIAS
VIMOS.2004-09-25T08:03:01.042.fits      BIAS
```

Four twilight flat fields:

```
VIMOS.2004-09-25T10:00:25.956.fits      IMG_SKY_FLAT
VIMOS.2004-09-25T10:01:09.806.fits      IMG_SKY_FLAT
VIMOS.2004-09-25T10:01:51.246.fits      IMG_SKY_FLAT
VIMOS.2004-09-25T10:03:13.433.fits      IMG_SKY_FLAT
```

Three dome flat fields:

```
VIMOS.2004-09-25T13:57:07.351.fits      IMG_SCREEN_FLAT
VIMOS.2004-09-25T13:57:52.041.fits      IMG_SCREEN_FLAT
VIMOS.2004-09-25T13:58:36.842.fits      IMG_SCREEN_FLAT
```

All the listed data are meant to belong to the same VIMOS quadrant.

In the following, it is also assumed for simplicity that the flag `suppress-prefix` is set to `TRUE` in the *EsoRex* configuration file, so that the product file names will just be identical to their product categories, with the extension `.fits`. Moreover, it is assumed that all the handled files (inputs and products) are located in the current directory. The only exception is represented by the standard calibration tables (*e.g.*, star catalogues), that here are assumed to be located under `/home/vimos/cal`.

The procedure is as follows:

First, a master bias is created with the recipe *vmbias* (see Section 7.2, page 63). The following set-of-frames may be prepared:

---

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

File: *bias.sof*

```
VIMOS.2004-09-25T08:00:27.821.fits    BIAS
VIMOS.2004-09-25T08:01:05.604.fits    BIAS
VIMOS.2004-09-25T08:01:44.091.fits    BIAS
VIMOS.2004-09-25T08:02:22.070.fits    BIAS
VIMOS.2004-09-25T08:03:01.042.fits    BIAS
```

The following command line can be given at the shell prompt:

```
esorex vmbias --StackMethod=Average bias.sof
```

The file `master_bias.fits`, containing the bias master calibration obtained from the input exposures, is created.

For creating the master flat field calibration, the recipe *vmimflatsky* (see Section 7.5, page 72) is applied to the four input twilight flat field exposures. The SOF may be prepared as follows:

File: *sky.sof*

```
VIMOS.2004-09-25T10:00:25.956.fits    IMG_SKY_FLAT
VIMOS.2004-09-25T10:01:09.806.fits    IMG_SKY_FLAT
VIMOS.2004-09-25T10:01:51.246.fits    IMG_SKY_FLAT
VIMOS.2004-09-25T10:03:13.433.fits    IMG_SKY_FLAT
master_bias.fits                      MASTER_BIAS
```

where the newly created master bias calibration is used.

The command line:

```
esorex vmimflatsky --StackMethod=Median sky.sof
```

will create the file `img_master_sky_flat.fits`, that can be used for the flat field correction of the scientific exposure.

Alternatively, a master sky flat field calibration may be created by combining the dome flat field exposures, carrying more accurate information about the high frequency fixed pattern noise, with the sky flat field exposures, carrying more reliable information on the large scale trends of the CCD illumination. For processing the raw screen flat field exposures, the recipe *vmimflatscreen* is used (see Section 7.4, page 69), and the SOF may be prepared as follows:

File: *dome.sof*

```
VIMOS.2004-09-25T13:57:07.351.fits    IMG_SCREEN_FLAT
VIMOS.2004-09-25T13:57:52.041.fits    IMG_SCREEN_FLAT
VIMOS.2004-09-25T13:58:36.842.fits    IMG_SCREEN_FLAT
master_bias.fits                      MASTER_BIAS
```

The command line:

```
esorex vmimflatscreen dome.sof
```

will create the two files `img_master_screen_flat.fits` and `img_combined_screen_flat.fits`. The master flat field will be added to the set-of-frames of the `vmimflatsky` recipe:

File: *sky.sof*

```
VIMOS.2004-09-25T10:00:25.956.fits    IMG_SKY_FLAT
VIMOS.2004-09-25T10:01:09.806.fits    IMG_SKY_FLAT
VIMOS.2004-09-25T10:01:51.246.fits    IMG_SKY_FLAT
VIMOS.2004-09-25T10:03:13.433.fits    IMG_SKY_FLAT
master_bias.fits                      MASTER_BIAS
img_master_screen_flat.fits           IMG_MASTER_SCREEN_FLAT
```

This will be called as before:

```
esorex vmimflatsky --StackMethod=Median sky.sof
```

With the master bias and the master flat field it is now possible to reduce the scientific observation. The set-of-frames may be defined as follows:

File: *science.sof*

```
VIMOS.2004-09-25T09:27:15.336.fits    IMG_SCIENCE
master_bias.fits                      MASTER_BIAS
img_master_sky_flat.fits              IMG_MASTER_SKY_FLAT
/home/vimos/cal/badpixel.1.tfits      CCD_TABLE
/home/vimos/cal/ipc_R.1.tfits         PHOTOMETRIC_TABLE
```

A bad-pixel table is specified in the set-of-frames, because in this example a bad-pixel correction will be requested when running the `vmimobsstare` recipe (see Section 7.11, page 89). The specified photometric table from the calibration directory tree carries the standard magnitude zeropoint for a given filter and a given instrument quadrant. This magnitude zeropoint will be copied to the header of the reduced image. Note that in this example it is assumed that the data belong to the 1st quadrant, and were obtained using the R filter.

The scientific exposure is then reduced by running:

```
esorex vmimobsstare --CleanBadPixel=TRUE science.sof
```

This will create the reduced scientific exposure, `img_science_reduced.fits`, and the list of detected objects, `img_galaxy_table.fits`.

Alternatively, since a standard star field observation from the same night is available, a more reliable photometric table may be computed. For this purpose, the following set-of-frames may be created:



File: *standard.sof*

```
VIMOS.2004-09-25T08:20:10.006.fits      IMG_STANDARD
master_bias.fits                        MASTER_BIAS
img_master_sky_flat.fits                IMG_MASTER_SKY_FLAT
/home/vimos/cal/phstd_stetson.tfits      PHOTOMETRIC_CATALOG
```

This is processed by the *vmimstandard* recipe (see Section 7.8, page 81):

```
esorex vmimstandard standard.sof
```

Three files are produced: the reduced image, *img\_standard\_reduced.fits*; the list of detected objects, *img\_galaxy\_table.fits*; and most important *img\_star\_match\_table.fits*, the list of identified standard stars, that includes the differences between the catalog magnitude and the instrumental magnitude for each detected standard star.

The star match table is then included in the set-of-frames of the *vmimcalphot* recipe (see Section 7.9, page 86):

File: *phot.sof*

```
img_star_match_table.fits                IMG_STAR_MATCH_TABLE
/home/vimos/cal/ipc_R.1.tfits            PHOTOMETRIC_TABLE
```

This is processed with:

```
esorex vmimcalphot phot.sof
```

generating a new photometric table, *photometric\_table.fits*, that will then replace the standard one in the *science.sof* set-of-frames shown above.

## 5.4 Example of MOS data reduction using EsoRex

A simple, typical MOS data reduction procedure is described here.<sup>7</sup> It is assumed that the following data are available:

One scientific exposure:

```
VIMOS.2004-09-27T02:39:11.479.fits      MOS_SCIENCE
```

One standard star exposure:

```
VIMOS.2004-09-27T03:12:12.006.fits      MOS_STANDARD
```

---

<sup>7</sup>The procedure using *Gasgano* is conceptually identical.

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Three flat field exposures obtained with the mask used for the scientific exposure:

VIMOS.2004-09-27T18:59:03.641.fits	MOS_SCREEN_FLAT
VIMOS.2004-09-27T19:00:07.828.fits	MOS_SCREEN_FLAT
VIMOS.2004-09-27T19:01:14.252.fits	MOS_SCREEN_FLAT

One arc lamp exposure obtained with the mask used for the scientific exposure:

VIMOS.2004-09-27T19:13:03.631.fits	MOS_ARC_SPECTRUM
------------------------------------	------------------

Three flat field exposures obtained with the mask used for the standard star exposure:

VIMOS.2004-09-27T19:22:22.308.fits	MOS_SCREEN_FLAT
VIMOS.2004-09-27T19:23:14.722.fits	MOS_SCREEN_FLAT
VIMOS.2004-09-27T19:24:52.651.fits	MOS_SCREEN_FLAT

One arc lamp exposure obtained with the mask used for the standard star exposure:

VIMOS.2004-09-27T19:33:44.097.fits	MOS_ARC_SPECTRUM
------------------------------------	------------------

Five bias exposures:

VIMOS.2004-09-27T08:00:27.821.fits	BIAS
VIMOS.2004-09-27T08:01:05.604.fits	BIAS
VIMOS.2004-09-27T08:01:44.091.fits	BIAS
VIMOS.2004-09-27T08:02:22.070.fits	BIAS
VIMOS.2004-09-27T08:03:01.042.fits	BIAS

All the listed data are meant to belong to the same VIMOS quadrant, with the same grism and filter in use.

All the listed data are meant to belong to the same VIMOS quadrant.

In the following, it is also assumed for simplicity that the flag `suppress-prefix` is set to `TRUE` in the *EsoRex* configuration file, so that the product file names will just be identical to their product categories, with the extension `.fits`. Moreover, it is assumed that all the handled files (inputs and products) are located in the current directory. The only exception is represented by the standard calibration tables (*e.g.*, line catalogues), that here are assumed to be located under `/home/vimos/cal`.

The procedure is as follows:

First, a master bias is created with the recipe `vmbias`, exactly as described in Section 5.3, page 30.

The product `master_bias.fits` is used in the reduction of the flat field, arc lamp, and scientific exposures.

In order to process the available flat field exposures, the recipe `vmflat` is used (see Section 7.13, page 97). The input SOF may be defined as follows:

File: *mosflat.sof*

VIMOS.2004-09-27T18:59:03.641.fits	MOS_SCREEN_FLAT
VIMOS.2004-09-27T19:00:07.828.fits	MOS_SCREEN_FLAT
VIMOS.2004-09-27T19:01:14.252.fits	MOS_SCREEN_FLAT
master_bias.fits	MASTER_BIAS
/home/vimos/cal/grs_LR_red.1.tfits	GRISM_TABLE

where it is assumed that the data belong to the 1st quadrant, and were obtained using the LR\_red grism.

The following command line can be given at the shell prompt:

```
esorex vmflat --StackMethod=Average mosflat.sof
```

The products are the MOS master screen flat, *mos\_master\_screen\_flat.fits*, and the non-normalised screen flat field, *mos\_combined\_screen\_flat.fits*. The latter should be specified in the set-of-frames associated to the *vmflatdisp* recipe (see Section 7.14, page 101), used to reduce the arc lamp exposure, and to determine the spectral distortions of the instrument:

File: *distortions.sof*

VIMOS.2004-09-27T19:13:03.631.fits	MOS_ARC_SPECTRUM
master_bias.fits	MASTER_BIAS
mos_combined_screen_flat.fits	MOS_COMBINED_SCREEN_FLAT
/home/vimos/cal/grs_LR_red.1.tfits	GRISM_TABLE
/home/vimos/cal/lcat_LR_red.1.tfits	LINE_CATALOG

This is processed by:

```
esorex vmflatdisp distortions.sof
```

The products are the extraction table, *extract\_table.fits*, that will make possible to extract the scientific slit spectra according to the determined instrument distortions; and the image of the extracted arc lamp slit spectra, *mos\_arc\_spectrum\_extracted.fits*, that is just used for quality control purposes.

The extraction table is specified in the last set-of-frames, the one associated to the recipe *vmflatstare* (see Section 7.15, page 108), used to reduce and extract the scientific spectra:

File: *objects.sof*

VIMOS.2004-09-27T02:39:11.479.fits	MOS_SCIENCE
master_bias.fits	MASTER_BIAS
extract_table.fits	EXTRACT_TABLE
/home/vimos/cal/grs_LR_red.1.tfits	GRISM_TABLE

This is processed by:

```
esorex vmmosobsstare objects.sof
```

The products are the extracted object spectra, `mos_science_reduced.fits`; the sky subtracted slit spectra, `mos_science_extracted.fits`; the sky slit and extracted spectra, `mos_science_sky.fits` and `mos_sky_reduced.fits`; and a couple of tables containing the identification of the extracted object spectra and their position along the slit, `object_table.fits` and `window_table.fits`.

If, as in this case, a standard star exposure is available, the same procedure would be repeated for the reduction of the standard star observation, using its associated calibrations. The only exception is in the final step, where the recipe `vmmosstandard` would be used instead of the recipe `vmmosobsstare` (see Section 7.18, page 117). The final SOF would look like the following:

File: *standard.sof*

```
VIMOS.2004-09-27T03:12:12.006.fits      MOS_STANDARD
master_bias.fits                        MASTER_BIAS
extract_table_std.fits                  EXTRACT_TABLE
/home/vimos/cal/grs_LR_red.1.tfits      GRISM_TABLE
/home/vimos/cal/extinct_table.tfits     EXTINCT_TABLE
/home/vimos/cal/gd108.tfits             STD_FLUX_TABLE
```

where the appropriate extraction table (different from the one associated to the scientific exposure) is specified, together with the atmospheric extinction table and the standard star spectral fluxes in  $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ .

This would be processed by:

```
esorex vmmosstandard standard.sof
```

which would generate, among other products, the spectro-photometric table, `mos_specphot_table.fits`. This table, that contains the instrument efficiency and response curves, should be added to the `objects.sof` set-of-frames, together with the atmospheric extinction table, as in the following:

File: *objects.sof*

```
VIMOS.2004-09-27T02:39:11.479.fits      MOS_SCIENCE
master_bias.fits                        MASTER_BIAS
extract_table.fits                      EXTRACT_TABLE
/home/vimos/cal/grs_LR_red.1.tfits      GRISM_TABLE
/home/vimos/cal/extinct_table.tfits     EXTINCT_TABLE
mos_specphot_table.fits                 MOS_SPECPHOT_TABLE
```

and processed by:

```
esorex vmmosobsstare --CalibrateFlux=true objects.sof
```

This run would then generate, in addition to the usual products of this recipe, also the file containing the extracted and flux calibrated spectra, `mos_science_flux_reduced.fits`.

## 5.5 Example of IFU data reduction using EsoRex

A simple, typical IFU data reduction procedure is described here.<sup>8</sup> It is assumed that the following data are available:

One scientific exposure:

```
VIMOS.2004-04-27T04:15:24.227.fits      IFU_SCIENCE
```

One standard star exposure:

```
VIMOS.2004-04-27T05:05:11.542.fits      IFU_STANDARD
```

Five bias exposures:

```
VIMOS.2004-04-27T08:00:27.821.fits      BIAS
VIMOS.2004-04-27T08:01:05.604.fits      BIAS
VIMOS.2004-04-27T08:01:44.091.fits      BIAS
VIMOS.2004-04-27T08:02:22.070.fits      BIAS
VIMOS.2004-04-27T08:03:01.042.fits      BIAS
```

Three flat field exposures:

```
VIMOS.2004-04-27T04:38:44.038.fits      IFU_SCREEN_FLAT
VIMOS.2004-04-27T04:40:32.250.fits      IFU_SCREEN_FLAT
VIMOS.2004-04-27T04:42:20.470.fits      IFU_SCREEN_FLAT
```

One arc lamp exposure:

```
VIMOS.2004-04-27T04:44:14.842.fits      IFU_ARC_SPECTRUM
```

All the listed data are meant to belong to the same VIMOS quadrant, with the same grism and filter in use.

In the following, it is also assumed for simplicity that the flag `suppress-prefix` is set to `TRUE` in the *EsoRex* configuration file, so that the product file names will just be identical to their product categories, with the extension `.fits`. Moreover, it is assumed that all the handled files (inputs and products) are located in the current directory. The only exception is represented by the standard calibration tables (*e.g.*, line catalogues), that here are assumed to be located under `/home/vimos/cal`.

The procedure is as follows:

First, a master bias is created with the recipe `vmbias`, exactly as described in Section 5.3, page 30.

The product `master_bias.fits` is used in the reduction of the flat field, arc lamp, and scientific exposures.

The flat field and the arc lamp exposures are processed to determine the extraction mask, the wavelength calibration, and the fiber-to-fiber relative transmission correction. The input set-of-frames may be defined as follows:

---

<sup>8</sup>The procedure using *Gasgano* is conceptually identical.

File: *calib.sof*

VIMOS.2004-04-27T04:38:44.038.fits	IFU_SCREEN_FLAT
VIMOS.2004-04-27T04:40:32.250.fits	IFU_SCREEN_FLAT
VIMOS.2004-04-27T04:42:20.470.fits	IFU_SCREEN_FLAT
VIMOS.2004-04-27T04:44:14.842.fits	IFU_ARC_SPECTRUM
master_bias.fits	MASTER_BIAS
/home/vimos/cal/lcat_HR_red.tfits	LINE_CATALOG
/home/vimos/cal/ifu_ident_HR_red.1.fits	IFU_IDENT

This will be processed with:

```
esorex vmifucalib calib.sof
```

For data quality control, the following products will be created: an image of the extracted and wavelength calibrated arc lamp spectra, *ifu\_arc\_spectrum\_extracted.fits*; an image of the extracted and wavelength calibrated flat field spectra, *ifu\_flat\_spectrum\_extracted.fits*; and an image obtained by the combination of all the raw input flat field exposures, *ifu\_master\_screen\_flat.fits*. For the purpose of reducing the scientific data, also the following files are created: the extraction mask, *ifu\_trace.fits*; the wavelength calibration, *ifu\_ids.fits*; and the relative transmission factors, *ifu\_transmission.fits*.

These files are included in the set-of-frames prepared for the scientific data reduction process:

File: *ifuscience.sof*

VIMOS.2004-04-27T04:15:24.227.fits	IFU_SCIENCE
master_bias.fits	MASTER_BIAS
ifu_ids.fits	IFU_IDS
ifu_trace.fits	IFU_TRACE
ifu_transmission.fits	IFU_TRANSMISSION

This will be processed with:

```
esorex vmifuscience ifuscience.sof
```

The following files will be created: an image containing the extracted, transmission corrected, and wavelength calibrated scientific spectra, *ifu\_science\_reduced.fits*, and an image of the reconstructed IFU field-of-view, *ifu\_fov.fits*.

If, as in this case, an IFU exposure of a standard star is available, it can be reduced using the recipe *vmifustandard*:

File: *ifustandard.sof*

VIMOS.2004-04-27T05:05:11.542.fits	IFU_STANDARD
master_bias.fits	MASTER_BIAS
ifu_ids.fits	IFU_IDS
ifu_trace.fits	IFU_TRACE
ifu_transmission.fits	IFU_TRANSMISSION
/home/vimos/cal/extinct_table.tfits	EXTINCT_TABLE
/home/vimos/cal/ltt4816.tfits	STD_FLUX_TABLE

This will be processed with:

```
esorex vmifustandard ifustandard.sof
```

This will generate, among other products, the spectro-photometric table, *ifu\_specphot\_table.fits*. This table, that contains the instrument efficiency and response curves, should be added to the *ifuscience.sof* set-of-frames, together with the atmospheric extinction table, as in the following:

File: *ifuscience.sof*

VIMOS.2004-04-27T04:15:24.227.fits	IFU_SCIENCE
master_bias.fits	MASTER_BIAS
ifu_ids.fits	IFU_IDS
ifu_trace.fits	IFU_TRACE
ifu_transmission.fits	IFU_TRANSMISSION
/home/vimos/cal/extinct_table.tfits	EXTINCT_TABLE
ifu_specphot_table.fits	IFU_SPECPHOT_TABLE

and processed by:

```
esorex vmifuscience --CalibrateFlux=true ifuscience.sof
```

This run would then generate, in addition to the usual products of this recipe, also the file containing the extracted and flux calibrated IFU spectra, *ifu\_science\_flux\_reduced.fits*.

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## 5.6 Known problems

The following is a list of currently-known issues with VIMOS recipes, and workarounds, if available:

**The spatial curvature model** may not be determined accurately from MOS flat field exposures by recipes *vmflat* and *vmflatdisp* if the slit spectra display any spatial overlap, or if spectral multiplexing is present: the confusion introduced at the edges of the slit spectra may strongly bias the tracing task. A simple solution to this problem is not yet available.

**The wavelength calibration** may not be determined accurately from MOS arc lamp exposures by recipe *vmflatdisp* if the first-guess distortion models contained in the headers of the input files are too far from the real instrument distortions, or if spectral multiplexing is present. In such cases, setting the recipe parameter *RefineIDS* to "true" may help to identify correctly the available arc lamp reference lines; if even this fails, the *LineIdent* parameter may be set to "Blind", attempting to identify the arc lamp lines with a pattern-recognition algorithm. In such problematic cases, a step-by-step approach may be advisable: first the best recipe parameters for an acceptable local spectral extraction are determined, and only then it may be attempted to add the global distortion models fitting. The obtained global models, written to the header of the output *extraction table* (see Table 7.14.3, page 103) may be iterated, using them as new and more accurate first-guesses for a more standard use of the *vmflatdisp* recipe. It will surely be advantageous, when accurate first-guess models are available, to specify a relatively small search window (about 5 or 6 pixels) for the arc lamp lines.

**The spectral fringing correction** performed by recipe *vmflatobsjitter* involves only a sky fringing subtraction, and therefore is of limited help in the case of bright object spectra.

**The atmospheric extinction table** made available in the static calibration directories (see Table 7.18.2, page 118), is based on data obtained at La Silla. This table may be replaced with another having the same structure: the wavelengths at which the atmospheric extinction is given can be chosen freely, since all the scientific data reduction recipes (*vmflatstandard*, *vmflatscience*, *vmflatstandard*, *vmflatobsstare*, *vmflatobsjitter* and *vmflatphot*) interpolate the available values as necessary.

**The IFU fiber identification** performed by recipe *vmflatcalib* appears to be negatively affected by changes in temperature. If in the recipe products more than about 50 fibers appear to be "lost" in one pseudo-slit, it may help to rerun the recipe using the "blind" fiber identification method: this method is always triggered if no fiber identification table is specified in the input set-of-frames.

**Zeropoint and color term determination** are not reliably determined by the recipe *vmflatstandard* if they are requested simultaneously.

**The filter/grism combination OS\_red/MR** is not supported by the IFU and MOS data reduction recipes.



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## 6 VIMOS data

VIMOS data can be separated into *raw* frames and *product* frames. Raw frames are the unprocessed output of the VIMOS instrument observations, while product frames are either the result of the VIMOS pipeline processing (as reduced frames, master calibration frames, etc.), or are outsourced (as standard stars catalogs, lists of grism characteristics, etc.).

Any raw or product frame can be classified on the basis of a set of keywords read from its header. Data classification is based on FITS keyword values. In the case of raw frames, classification can be defined by looking at three keyword values: DPR TYPE, DPR CATG, and DPR TECH. In the case of data products, the classification of the frame is stored into the hierarchical keyword PRO CATG.

The association of a raw frame with calibration data (*e.g.*, of a science frame with a master bias frame) can be obtained by matching the values of a different set of FITS keywords.

Each kind of raw frame is typically associated to a single VIMOS pipeline recipe, *i.e.*, the recipe assigned to the reduction of that specific frame type. In the pipeline environment this recipe would be launched automatically. In some cases two recipes are assigned, one meant for the reduction of a single frame of that type, and the other for the reduction of a *stack* of frames of the same type, as happens in the case of jittered science observations.

A product frame may be input to more than one VIMOS pipeline recipe, but it may be created by just one pipeline recipe (with the same exceptions mentioned above). In the automatic pipeline environment a product data frame alone wouldn't trigger the launch of any recipe.

In the following all raw and product VIMOS data frames are listed, together with the keywords used for their classification and correct association. The indicated *DO category* is a label assigned to any data type after it has been classified, which is then used to identify the frames listed in the *set-of-frames* (see Section 5.2.2, page 27).

### 6.1 Raw frames

Raw frames can be distinguished in *general* frames, *direct imaging* frames, *MOS* frames and *IFU* frames. Their intended use is implicitly defined by the assigned recipe.

#### 6.1.1 General frames

These are data that are in principle independent of the instrument mode (direct imaging, MOS, or IFU), as is the case for bias and dark exposures. The keyword `ESO INS MODE` is set accordingly to 'IMG' for direct imaging frames, and to 'MOS' for any calibration associated to spectroscopy (either MOS or IFU), to indicate the intended use for the data.

- **Bias:**

DO category: BIAS

Processed by: `vbias`

Classification keywords:

Association keywords:

Note:

DPR CATG = CALIB  
DPR TYPE = BIAS  
DPR TECH = IMAGE

INS MODE  
OCS CON QUAD  
DET CHIP1 ID  
DET WIN1 NY  
DET WIN1 BINX  
DET WIN1 BINY  
DET READ MODE  
DET READ SPEED  
DET READ CLOCK

Instrument mode  
Quadrant used  
Chip identification  
No of pixels in y  
Binning along X  
Binning along Y  
Readout method  
Readout speed  
Readout clock pattern

- **Dark current:**

DO category: DARK  
Processed by: vmdark

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

Association keywords:  
INS MODE  
OCS CON QUAD  
DET CHIP1 ID  
DET WIN1 NY  
DET WIN1 BINX  
DET WIN1 BINY  
DET READ MODE  
DET READ SPEED  
DET READ CLOCK

Note:  
Instrument mode  
Quadrant used  
Chip identification  
No of pixels in y  
Binning along X  
Binning along Y  
Readout method  
Readout speed  
Readout clock pattern

- **Screen flat field for gain determination and bad pixels detection:**

DO category: DETECTOR\_PROPERTIES  
Processed by: vmdet

Classification keywords:  
DPR CATG = CALIB  
DPR TYPE = FLAT, LAMP  
DPR TECH = IMAGE or MOS  
TPL ID = VIMOS\_img\_tec\_DetLin  
or VIMOS\_mos\_tec\_DetLin

Association keywords:  
INS MODE  
OCS CON QUAD  
DET CHIP1 ID  
DET WIN1 NY  
DET WIN1 BINX  
DET WIN1 BINY  
DET READ MODE  
DET READ SPEED  
DET READ CLOCK

Note:  
Instrument mode  
Quadrant used  
Chip identification  
No of pixels in y  
Binning along X  
Binning along Y  
Readout method  
Readout speed  
Readout clock pattern

### 6.1.2 Direct imaging frames

The direct imaging mode is used to record signal without using any grism.

- **Exposure of calibration mask:**

DO category: MASK\_TO\_CCD

Processed by: vmmasktoccd

Classification keywords:

DPR CATG = CALIB

DPR TYPE = OTHER,LAMP

DPR TECH = IMAGE

TPL ID = VIMOS\_img\_tec\_MaskToCcd

Association keywords:

INS MODE

OCS CON QUAD

INS ADF ID

INS FILT[1-4] ID

DET CHIP1 ID

DET WIN1 NY

DET WIN1 BINX

DET WIN1 BINY

DET READ MODE

DET READ SPEED

DET READ CLOCK

Note:

Instrument mode

Quadrant used

ADF file ID

Filter ID on each beam

Chip identification

No of pixels in y

Binning along X

Binning along Y

Readout method

Readout speed

Readout clock pattern

- **Preimaging for MOS mask preparation:**

DO category: IMG\_PREIMAGING

Processed by: vmimpreimaging

Classification keywords:

DPR CATG = SCIENCE

DPR TYPE = OBJECT

DPR TECH = IMAGE,PRE

Association keywords:

INS MODE

OCS CON QUAD

INS FILT[1-4] ID

DET CHIP1 ID

DET WIN1 NY

DET WIN1 BINX

DET WIN1 BINY

DET READ MODE

DET READ SPEED

DET READ CLOCK

Note:

Instrument mode

Quadrant used

Filter ID on each beam

Chip identification

No of pixels in y

Binning along X

Binning along Y

Readout method

Readout speed

Readout clock pattern

- **Twilight flat field:**

DO category: IMG\_SKY\_FLAT

Processed by: vmimflatsky

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Classification keywords:

DPR CATG = CALIB  
DPR TYPE = FLAT,SKY  
DPR TECH = IMAGE

Association keywords:

INS MODE  
OCS CON QUAD  
INS FILT[1-4] ID  
DET CHIP1 ID  
DET WIN1 NY  
DET WIN1 BINX  
DET WIN1 BINY  
DET READ MODE  
DET READ SPEED  
DET READ CLOCK

Note:

Instrument mode  
Quadrant used  
Filter ID on each beam  
Chip identification  
No of pixels in y  
Binning along X  
Binning along Y  
Readout method  
Readout speed  
Readout clock pattern

• **Screen flat field:**

DO category: IMG\_SCREEN\_FLAT  
Processed by: vmimflatscreen

Classification keywords:

DPR CATG = CALIB  
DPR TYPE = FLAT,LAMP  
DPR TECH = IMAGE  
TPL ID = VIMOS\_img\_cal\_ScreenFlat

Association keywords:

INS MODE  
OCS CON QUAD  
INS FILT[1-4] ID  
INS LAMP[1-5] ID  
INS LAMP[1-5] STATE  
DET CHIP1 ID  
DET WIN1 NY  
DET WIN1 BINX  
DET WIN1 BINY  
DET READ MODE  
DET READ SPEED  
DET READ CLOCK

Note:

Instrument mode  
Quadrant used  
Filter ID on each beam  
Calib. lamps ID  
Lamp state  
Chip identification  
No of pixels in y  
Binning along X  
Binning along Y  
Readout method  
Readout speed  
Readout clock pattern

• **Standard stars field:**

DO category: IMG\_STANDARD  
Processed by: vmimstandard

Classification keywords:

DPR CATG = CALIB  
DPR TYPE = STD  
DPR TECH = IMAGE

Association keywords:

INS MODE  
OCS CON QUAD  
INS FILT[1-4] ID  
DET CHIP1 ID  
DET WIN1 NY  
DET WIN1 BINX  
DET WIN1 BINY

Note:

Instrument mode  
Quadrant used  
Filter [1-4] on each beam  
Chip identification  
No of pixels in y  
Binning along X  
Binning along Y

DET READ MODE	Readout method
DET READ SPEED	Readout speed
DET READ CLOCK	Readout clock pattern

• **Astrometric stars field:**

DO category: IMG\_Astrometry  
 Processed by: vmskyccd

Classification keywords:	Association keywords:	Note:
DPR CATG = CALIB	INS MODE	Instrument mode
DPR TYPE = Astrometry	OCS CON QUAD	Quadrant used
DPR TECH = IMAGE	OBS TARG NAME	Astrometric field used
	INS FILT[1-4] ID	Filter ID on each beam
	DET CHIP1 ID	Chip identification
	DET WIN1 NY	No of pixels in y
	DET WIN1 BINX	Binning along X
	DET WIN1 BINY	Binning along Y
	DET READ MODE	Readout method
	DET READ SPEED	Readout speed
	DET READ CLOCK	Readout clock pattern

• **Scientific observation:**

DO category: IMG\_Science  
 Processed by: vmimobsstare, vmimobsjitter

Classification keywords:	Association keywords:	Note:
DPR CATG = Science	INS MODE	Instrument mode
DPR TYPE = OBJECT	OCS CON QUAD	Quadrant used
DPR TECH = IMAGE	INS FILT[1-4] ID	Filter ID on each beam
	DET CHIP1 ID	Chip identification
	DET WIN1 NY	No of pixels in y
	DET WIN1 BINX	Binning along X
	DET WIN1 BINY	Binning along Y
	DET READ MODE	Readout method
	DET READ SPEED	Readout speed
	DET READ CLOCK	Readout clock pattern

### 6.1.3 MOS frames

The Multi-Object Spectroscopy mode is used to obtain simultaneous spectra from several objects in the field-of-view.

- **Screen flat field:**

DO category: MOS\_SCREEN\_FLAT

Processed by: vmspflat

Classification keywords:	Association keywords:	Note:
DPR CATG = CALIB	INS MODE	Instrument mode
DPR TYPE = FLAT,LAMP	OCS CON QUAD	Quadrant used
DPR TECH = MOS	INS FILT[1-4] NAME	Filter name on each beam
TPL ID = VIMOS_mos_cal_ScreenFlat	INS GRIS[1-4] ID	Grism ID on each beam
or VIMOS_mos_tec_Starttr	INS MASK[1-4] ID	Mask ID on each beam
	INS MSHU[1-4] MODE	Mask shutter mode
	INS LAMP[1-5] ID	Calib. lamps ID
	INS LAMP[1-5] STATE	Lamp state
	DET CHIP1 ID	Chip identification
	DET WIN1 NY	No of pixels in y
	DET WIN1 BINX	Binning along X
	DET WIN1 BINY	Binning along Y
	DET READ MODE	Readout method
	DET READ SPEED	Readout speed
	DET READ CLOCK	Readout clock pattern

- **Arc lamp spectra:**

DO category: MOS\_ARC\_SPECTRUM

Processed by: vmspcaldisp

Classification keywords:	Association keywords:	Note:
DPR CATG = CALIB	INS MODE	Instrument mode
DPR TYPE = WAVE,LAMP	OCS CON QUAD	Quadrant used
DPR TECH = MOS	INS FILT[1-4] NAME	Filter name on each beam
	INS GRIS[1-4] ID	Grism ID on each beam
	INS MASK[1-4] ID	Mask ID on each beam
	INS MSHU[1-4] MODE	Mask shutter mode
	INS LAMP[1-5] ID	Calib. lamps ID
	INS LAMP[1-5] STATE	Lamp state
	DET CHIP1 ID	Chip identification
	DET WIN1 NY	No of pixels in y
	DET WIN1 BINX	Binning along X
	DET WIN1 BINY	Binning along Y

DET READ MODE	Readout method
DET READ SPEED	Readout speed
DET READ CLOCK	Readout clock pattern

- **Standard star spectrum:**

DO category: MOS\_STANDARD  
 Processed by: vmmosstandard

Classification keywords:

DPR CATG = CALIB  
 DPR TYPE = STD  
 DPR TECH = MOS

Association keywords:

INS MODE	Instrument mode
OCS CON QUAD	Quadrant used
INS FILT[ 1-4 ] NAME	Filter name on each beam
INS GRIS[ 1-4 ] ID	Grism ID on each beam
INS MASK[ 1-4 ] ID	Mask ID on each beam
INS MSHU[ 1-4 ] MODE	Mask shutter mode
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y
DET READ MODE	Readout method
DET READ SPEED	Readout speed
DET READ CLOCK	Readout clock pattern

Note:

- **Scientific observation:**

DO category: MOS\_SCIENCE  
 Processed by: vmmosobsstare, vmmosobsjitter

Classification keywords:

DPR CATG = SCIENCE  
 DPR TYPE = OBJECT  
 DPR TECH = MOS

Association keywords:

INS MODE	Instrument mode
OCS CON QUAD	Quadrant used
INS FILT[ 1-4 ] NAME	Filter name on each beam
INS GRIS[ 1-4 ] ID	Grism ID on each beam
INS MASK[ 1-4 ] ID	Mask ID on each beam
INS MSHU[ 1-4 ] MODE	Mask shutter mode
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y
DET READ MODE	Readout method
DET READ SPEED	Readout speed
DET READ CLOCK	Readout clock pattern

Note:

#### 6.1.4 IFU frames

The IFU mode is used to get in a spatially continuous way simultaneous spectra from a selected sky region.

- **Screen flat field:**

DO category: IFU\_SCREEN\_FLAT

Processed by: vmifucalib

Classification keywords:

DPR CATG = CALIB

DPR TYPE = FLAT,LAMP

DPR TECH = IFU

Association keywords:

INS MODE

OCS CON QUAD

INS FILT[1-4] NAME

INS GRIS[1-4] ID

INS LAMP[1-5] ID

INS LAMP[1-5] STATE

INS IFUE MAG

INS IFUS MODE

DET CHIP1 ID

DET WIN1 NY

DET WIN1 BINX

DET WIN1 BINY

DET READ MODE

DET READ SPEED

DET READ CLOCK

Note:

Instrument mode

Quadrant used

Filter name on each beam

Grism ID on each beam

Calib. lamps ID

Lamp state

IFU magnification

IFU shutter mode

Chip identification

No of pixels in y

Binning along X

Binning along Y

Readout method

Readout speed

Readout clock pattern

- **Arc lamp spectra:**

DO category: IFU\_ARC\_SPECTRUM

Processed by: vmifucalib

Classification keywords:

DPR CATG = CALIB

DPR TYPE = WAVE,LAMP

DPR TECH = IFU

Association keywords:

INS MODE

OCS CON QUAD

INS FILT[1-4] NAME

INS GRIS[1-4] ID

INS LAMP[1-5] ID

INS LAMP[1-5] STATE

INS IFUE MAG

INS IFUS MODE

DET CHIP1 ID

DET WIN1 NY

DET WIN1 BINX

DET WIN1 BINY

DET READ MODE

Note:

Instrument mode

Quadrant used

Filter name on each beam

Grism ID on each beam

Calib. lamps ID

Lamp state

IFU magnification

IFU shutter mode

Chip identification

No of pixels in y

Binning along X

Binning along Y

Readout method



DET READ SPEED	Readout speed
DET READ CLOCK	Readout clock pattern

- **Standard star spectra:**

DO category: IFU\_STANDARD  
 Processed by: vmifustandard

Classification keywords:

DPR CATG = CALIB  
 DPR TYPE = STD  
 DPR TECH = IFU

Association keywords:

INS MODE	Instrument mode
OCS CON QUAD	Quadrant used
INS FILT[1-4] NAME	Filter name on each beam
INS GRIS[1-4] ID	Grism ID on each beam
INS IFUE MAG	IFU magnification
INS IFUS MODE	IFU shutter mode
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y
DET READ MODE	Readout method
DET READ SPEED	Readout speed
DET READ CLOCK	Readout clock pattern

Note:

- **Scientific observation:**

DO category: IFU\_SCIENCE  
 Processed by: vmifuscience

Classification keywords:

DPR CATG = SCIENCE  
 DPR TYPE = OBJECT  
 DPR TECH = IFU

Association keywords:

INS MODE	Instrument mode
OCS CON QUAD	Quadrant used
INS FILT[1-4] NAME	Filter name on each beam
INS GRIS[1-4] ID	Grism ID on each beam
INS IFUE MAG	IFU magnification
INS IFUS MODE	IFU shutter mode
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y
DET READ MODE	Readout method
DET READ SPEED	Readout speed
DET READ CLOCK	Readout clock pattern

Note:

## 6.2 Product frames

As with raw frames, product frames can be distinguished in *general* frames, *direct imaging* frames, *MOS* frames, and *IFU* frames. These frames are classified by *Gasgano* [7] according to their own DO category (keyword PRO CATG), assigned to them at creation time. For this reason no classification keyword is listed in this section. The name of the recipe (or recipes) used to create a given product is given here.

### 6.2.1 General frames

- **Master bias:**

DO category: MASTER\_BIAS

Created by: vmbias

Association keywords:

OCS CON QUAD  
DET CHIP1 ID  
DET WIN1 NY  
DET WIN1 BINX  
DET WIN1 BINY  
DET READ MODE  
DET READ SPEED  
DET READ CLOCK

Note:

Quadrant used  
Chip identification  
No of pixels in y  
Binning along X  
Binning along Y  
Readout method  
Readout speed  
Readout clock pattern

- **Master dark:**

DO category: MASTER\_DARK

Created by: vmdark

Association keywords:

OCS CON QUAD  
DET CHIP1 ID  
DET WIN1 NY  
DET WIN1 BINX  
DET WIN1 BINY  
DET READ MODE  
DET READ SPEED  
DET READ CLOCK

Note:

Quadrant used  
Chip identification  
No of pixels in y  
Binning along X  
Binning along Y  
Readout method  
Readout speed  
Readout clock pattern

- **List of bad pixels positions:**

DO category: CCD\_TABLE

Created by: vmdet

Association keywords:	Note:
OCS CON QUAD	Instrument quadrant
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y
DET READ MODE	Readout method
DET READ SPEED	Readout speed
DET READ CLOCK	Readout clock pattern

## 6.2.2 Direct imaging frames

- **Master sky flat field:**

DO category: IMG\_MASTER\_SKY\_FLAT  
Created by: vmimflatsky

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] ID	Filter ID for beam 1 to 4
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y
DET READ MODE	Readout method
DET READ SPEED	Readout speed
DET READ CLOCK	Readout clock pattern

- **Master screen flat field:**

DO category: IMG\_MASTER\_SCREEN\_FLAT  
Created by: vmimflatscreen

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] ID	Filter ID for beam 1 to 4
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y
DET READ MODE	Readout method
DET READ SPEED	Readout speed
DET READ CLOCK	Readout clock pattern

- **Combined screen flat field:**

DO category: IMG\_COMBINED\_SCREEN\_FLAT

Created by: vmimflatscreen

No association rules are defined for a combined screen flat field. This dataset is not used by any pipeline recipe, and is only created for data quality control purposes.

- **Reduced scientific observation:**

DO category: IMG\_SCIENCE\_REDUCED

Created by: vmimpreimaging, vmimobsstare, vmimobsjitter

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] ID	Filter ID for beam 1 to 4
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y

- **Reduced standard stars field:**

DO category: IMG\_STANDARD\_REDUCED

Created by: vmimstandard

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] ID	Filter ID for beam 1 to 4
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y

- **Sky + sky fringes map:**

DO category: IMG\_FRINGES

Created by: vmimobsjitter

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] ID	Filter ID for beam 1 to 4
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y

- **List of detected sources:**

DO category: IMG\_GALAXY\_TABLE

Created by: vmimobsstare, vmimobsjitter, vmimstandard

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] ID	Filter ID for beam 1 to 4

- **List of identified stars:**

DO category: IMG\_STAR\_MATCH\_TABLE

Created by: vmimstandard

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] ID	Filter ID for beam 1 to 4

- **Astrometric catalog:**

DO category: ASTROMETRIC\_TABLE

Created by: *external*

Association keywords:	Note:
OBS TARG NAME	Astrometric field name

- **Coefficients for photometric calibration:**

DO category: PHOTOMETRIC\_TABLE

Created by: vmimcalphot

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] ID	Filter ID for beam 1 to 4

- **Photometric catalog:**

DO category: PHOTOMETRIC\_CATALOG

Created by: *external*

*No association keyword required.*

### 6.2.3 MOS frames

- **Master screen flat field:**

DO category: MOS\_MASTER\_SCREEN\_FLAT

Created by: vmspflat

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
INS MASK[1-4] ID	Mask ID for beam 1 to 4
INS MSHU[1-4] MODE	Mask shutter mode for beam 1 to 4
DET NAME	Name of detector
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y

- **Combined screen flat field:**

DO category: MOS\_COMBINED\_SCREEN\_FLAT

Created by: vmspflat

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
INS MASK[1-4] ID	Mask ID for beam 1 to 4
INS MSHU[1-4] MODE	Mask shutter mode for beam 1 to 4
DET NAME	Name of detector
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y

- **Calibration lamp lines catalog:**

DO category: LINE\_CATALOG

Created by: *external*

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS GRIS[1-4] ID	Grism ID for beam 1 to 4

- **Position of detected objects on extracted slit spectra:**

DO category: WINDOW\_TABLE

Created by: *vmmosobsstare*, *vmmosobsjitter*

No association rules are defined for a window table, because this dataset is not used by any pipeline recipe.

- **Identification of extracted spectra:**

DO category: OBJECT\_TABLE

Created by: *vmmosobsstare*, *vmmosobsjitter*

No association rules are defined for an object table, because this dataset is not used by any pipeline recipe.

- **Grism dependent parameters:**

DO category: GRISM\_TABLE

Created by: *external*

Association keywords:

OCS CON QUAD

INS FILT[1-4] NAME

INS GRIS[1-4] ID

Note:

Instrument quadrant

Filter name for beam 1 to 4

Grism ID for beam 1 to 4

- **Spectral extraction parameters:**

DO category: EXTRACT\_TABLE

Created by: *vmspcaldisp*

No association rules are defined for an extraction table. This dataset is not used within the on-line pipeline process. The user should ensure that the correct extraction table is specified when calling the recipes *vmspcaldisp*, *vmmosobsstare* and *vmmosobsjitter*.

- **Extracted spectra:**

DO category: MOS\_SCIENCE\_REDUCED

Created by: *vmmosobsstare*, *vmmosobsjitter*

Association keywords:

OCS CON QUAD

INS FILT[1-4] NAME

INS GRIS[1-4] ID

INS MASK[1-4] ID

INS MSHU[1-4] MODE

DET CHIP1 ID

DET WIN1 NY

DET WIN1 BINX

DET WIN1 BINY

Note:

Quadrant used

Filter name for beam 1 to 4

Grism ID on each beam

Mask ID for beam 1 to 4

Mask shutter mode for beam 1 to 4

Chip identification

No of pixels in y

Binning along X

Binning along Y

- **Extracted and flux calibrated spectra:**

DO category: MOS\_SCIENCE\_FLUX\_REDUCED

Created by: vmmosobsstare, vmmosobsjitter

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
INS MASK[1-4] ID	Mask ID for beam 1 to 4
INS MSHU[1-4] MODE	Mask shutter mode for beam 1 to 4
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y

- **Extracted sky spectra:**

DO category: MOS\_SKY\_REDUCED

Created by: vmmosobsstare, vmmosobsjitter

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
INS MASK[1-4] ID	Mask ID for beam 1 to 4
INS MSHU[1-4] MODE	Mask shutter mode for beam 1 to 4
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y

- **Atmospheric extinction:**

DO category: EXTINGT\_TABLE

Created by: *external*

*No association keyword required.*



- **Sky + sky fringes map:**

DO category: MOS\_FRINGES\_SKY

Created by: vmmosobsjitter

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
INS MASK[1-4] ID	Mask ID for beam 1 to 4
INS MSHU[1-4] MODE	Mask shutter mode for beam 1 to 4
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y

- **Sky fringes map:**

DO category: MOS\_FRINGES

Created by: vmmosobsjitter

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
INS MASK[1-4] ID	Mask ID for beam 1 to 4
INS MSHU[1-4] MODE	Mask shutter mode for beam 1 to 4
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y

- **Extracted standard star spectrum:**

DO category: MOS\_STANDARD\_REDUCED

Created by: vmmosstandard

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
INS MASK[1-4] ID	Mask ID for beam 1 to 4
INS MSHU[1-4] MODE	Mask shutter mode for beam 1 to 4
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y

DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y

- **Spectro-photometric standard star fluxes:**

DO category: STD\_FLUX\_TABLE

Created by: *external*

Association keywords:	Note:
OBS TARG NAME	Standard star name

- **Spectral response and instrument efficiency:**

DO category: MOS\_SPECPHOT\_TABLE

Created by: *vmmosstandard*

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
DET CHIP1 ID	Chip identification

## 6.2.4 IFU frames

- **Master screen flat field:**

DO category: IFU\_MASTER\_SCREEN\_FLAT

Created by: *vmifucalib*

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS IFUE MAG	IFU magnification
INS IFUS MODE	IFU shutter mode
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
DET NAME	Name of detector
DET CHIP1 ID	Chip identification
DET WIN1 NY	No of pixels in y
DET WIN1 BINX	Binning along X
DET WIN1 BINY	Binning along Y

- **Spectral response and instrument efficiency:**

DO category: IFU\_SPECPHOT\_TABLE

Created by: *vmifustandard*

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
DET CHIP1 ID	Chip identification

- **Reconstructed field-of-view:**

DO category: IFU\_FOV

Created by: *vmifuscience, vmifustandard*

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS IFUE MAG	IFU magnification
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
DET CHIP1 ID	Chip identification

- **Sky spectrum:**

DO category: IFU\_SCIENCE\_SKY

Created by: *vmifustandard*

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS IFUE MAG	IFU magnification
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
DET CHIP1 ID	Chip identification

- **Standard star spectrum:**

DO category: IFU\_STANDARD\_EXTRACTED

Created by: *vmifustandard*

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS IFUE MAG	IFU magnification
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
DET CHIP1 ID	Chip identification

- **Reduced standard star fiber spectra:**

DO category: IFU\_STANDARD\_REDUCED

Created by: vmifustandard

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS IFUE MAG	IFU magnification
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
DET CHIP1 ID	Chip identification

- **Reduced science spectra:**

DO category: IFU\_SCIENCE\_REDUCED

Created by: vmifuscience

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS IFUE MAG	IFU magnification
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam
DET CHIP1 ID	Chip identification

- **IFU fiber identification file:**

DO category: IFU\_IDENT

Created by: *external*

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS GRIS[1-4] ID	Grism ID on each beam

- **IFU wavelength calibration:**

DO category: IFU\_IDS

Created by: vmifucalib

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam

- **IFU extraction mask:**

DO category: IFU\_TRACE  
Created by: vmifucalib

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS FILT[1-4] NAME	Filter name for beam 1 to 4
INS GRIS[1-4] ID	Grism ID on each beam

- **IFU relative transmission factors:**

DO category: IFU\_TRANSMISSION  
Created by: vmifucalib

Association keywords:	Note:
OCS CON QUAD	Quadrant used
INS GRIS[1-4] ID	Grism ID on each beam

## 7 Pipeline recipes

In this section the usage of the VIMOS pipeline recipes is described in detail.

### 7.1 vmdet

The VIMOS pipeline recipe *vmdet* is used to estimate the *read-out-noise* (RON) and the gain of the CCD, and to determine the positions of the bad pixels.

The input SOF should contain at least five pairs of flat field exposures, all belonging to the same quadrant, each pair corresponding to a different exposure time. The flat fields can be produced either in imaging or in MOS mode. In MOS mode a HR grism is used, in order to illuminate the CCD also beyond the central region used in direct imaging mode, but no mask is inserted at the telescope focal plane. This type of exposure cannot really be considered a *spectral* flat field, because the CCD is exposed to “white” light (*i.e.*, without a wavelength dependency along the dispersion direction). The flat fields generated for the purpose of determining the detector properties (produced by the technical templates VIMOS\_img\_tec\_DetLin and VIMOS\_mos\_tec\_DetLin) are assigned the DO category DETECTOR\_PROPERTIES, to distinguish them from the more common IMG\_SCREEN\_FLAT or MOS\_SCREEN\_FLAT that are used to produce master calibrations.

All the files that must be included in the input SOF are listed in table 7.1.1.

DO category	Type	Explanation	Required
DETECTOR_PROPERTIES	Raw frame	Flat field exposure	✓
MASTER_BIAS	Calibration	Master bias	✓

Table 7.1.1: *Input files for the vmdet recipe.*

The products of the *vmdet* recipe are shown in Table 7.1.2. Only the primary product, the bad pixel table, is copied (or moved) to the product directory. Other products are generated only on request (typically for debug purposes) and are not assigned a DO category as they would not be used anywhere in further data processing steps.

File name	DO category	Type	Explanation
ccd_table.fits	CCD_TABLE	FITS	Bad pixel table
bad_pixel_map.fits		FITS	Bad pixel image
error_image.fits		FITS	Error image

Table 7.1.2: *Products of the vmdet recipe.*

The *vmdet* parameters are listed in Table 7.1.3.

A more complete description of the parameters meaning is also given:

**CreateBadPixelMap:** If this parameter is set, a bad pixel image reflecting the content of the created bad pixel

Parameter	Possible values	Explanation
DetectionMode	Intolerant Tolerant	All pixels with anomalous response are bad Only non-linear pixels are bad
DetectionThreshold	<i>float</i> (sigma)	Tolerance on bad pixel detection
CreateBadPixelMap	true false	Create a bad pixel image Do not create it
CreateErrorImage	true false	Create an error image Do not create it

Table 7.1.3: *vmDET* parameters.

table is created. This may be useful for determining the optimal settings for the parameters *DetectionMode* and *DetectionThreshold*, viewing the frequency of “bad” pixels and their spatial distribution.

**CreateErrorImage:** If this parameter is set an error image is created. The error image contains the values of the RMS of the residuals for each linear fitting done for bad pixel detection.

**DetectionMode:** Method used for detecting bad pixels. Possible settings are:

**Intolerant:** A pixel is flagged as “bad” when the slope of the linear fit of each image median exposure level versus the corresponding pixel values deviates from the local average of all slopes by more than the threshold specified in *DetectionThreshold*.

**Tolerant:** The same method as in the “*Intolerant*” *DetectionMode* is applied, but before linear fitting the measured pixel values are normalised so that the maximum pixel value is equal to the maximum median exposure level.

**DetectionThreshold:** Number of standard deviations from the mean slope of the CCD response, that are necessary for classifying a pixel as “bad”.

A description of the algorithms used in this recipe is given in Section 9.11, page 148.

## 7.2 vmbias

The VIMOS pipeline recipe *vmbias* is used to create a master bias frame from a set of raw bias frames. All the files that must be included in the input SOF are listed in Table 7.2.1.

DO category	Type	Explanation	Required
BIAS	Raw frame	Bias exposure	✓
CCD_TABLE	Calibration	Bad pixel table	

Table 7.2.1: *Input files for the vmbias recipe.*

A bad pixel table needs to be specified only if the cleaning of bad pixels is requested. In the calibration directories there is one CCD\_TABLE file for each quadrant, named *badpixel.q.tfits* (where *q* is the quadrant

number in the case of imaging data, and the quadrant number increased by 4 in the case of spectral data). Care should be taken in selecting the appropriate bad pixel tables for imaging and spectral instrument modes.

The only product of the *vmbias* recipe is the master bias, as shown in Table 7.2.2.

File name	DO category	Type	Explanation
master_bias.fits	MASTER_BIAS	FITS	Master bias

Table 7.2.2: *Product of the vmbias recipe.*

The *vmbias* parameters are described in Table 7.2.3.

Parameter	Possible values	Explanation
AllowSingleFrames	true false	A single input bias is also allowed More than one input bias is required
StackMethod	Average Median MinMax Ksigma Auto	Master bias is average of input biases Master bias is median of input biases Master bias is obtained with min-max rejection Master bias is obtained with K-sigma clipping Optimal combination of input biases
MinRejection	<i>int</i>	No. of lowest rejected values for rejection method
MaxRejection	<i>int</i>	No. of highest rejected values for rejection method
KSigmaLow	<i>float</i> (sigma)	Low threshold for K-sigma clipping method
KSigmaHigh	<i>float</i> (sigma)	High threshold for K-sigma clipping method
RemoveOverscan	true false	Remove overscan regions from master bias Keep overscan regions in master bias
CleanBadPixel	true false	Interpolate bad pixels on master bias No bad pixel correction
CleanCosmic	true false	Remove cosmic ray events from each bias No cosmic ray removal
ComputeQC	true false	Compute QC parameters Do not compute QC parameters

Table 7.2.3: *vmbias parameters.*

A more complete description of the parameters meaning is also given:

**AllowSingleFrames:** If this parameter is set, then a master bias is produced also from a single input bias. In this case the *StackMethod* is ignored.

**CleanBadPixel:** Bad pixel correction on the master bias. If this option is turned on, a bad pixel table should be specified in the input SOF (see Table 7.2.1). The bad pixel correction algorithm is described in Section 9.1, page 141.

**CleanCosmic:** Cosmic ray events removal from each input bias. The cosmic ray rejection algorithm is described in Section 9.2, page 142.



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**ComputeQC:** If this parameter is set, *Quality Control* (QC) parameters will be computed and written to the header of the output master bias and to an output QC PAF file named `qc0000.paf`. This file is not classified as a pipeline recipe product, as it is an intermediate dataset that in the standard pipeline operations would be translated into new entries in the QC log file. Currently the QC parameters computed by *vmbias* are:

- QC BIAS MEAN: Mean value of the 1600x1800 central pixels of the first raw bias listed in the SOF.
- QC BIAS MEDIAN: Median value of the 1600x1800 central pixels of the first raw bias listed in the SOF.
- QC BIAS RMS: The population standard deviation of the 1600x1800 central pixels of the first input bias.
- QC RON: Population standard deviation of the 1600x1800 central pixels of the difference between the first and the second raw biases listed in the SOF, divided by  $\sqrt{2}$ .
- QC BIAS FPN: The population standard deviation of the 1600x1800 central pixels of the difference between the first raw bias and the second raw bias shifted by 10x10 pixels, is computed. This is the combination of fixed-pattern-noise and read-out-noise (scaled by  $\sqrt{2}$ ). The read-out-noise contribution (QC RON) is then quadratically subtracted from the total noise.
- QC BIAS STRUCT: The population standard deviation of the 1600x1800 central pixels of the first raw bias (QC BIAS RMS) is the combination of structure, fixed-pattern-noise, and read-out-noise. The read-out-noise (QC RON) and the fixed-pattern-noise (QC BIAS FPN) contributions are quadratically subtracted from this value.
- QC BIAS MASTER MEAN: Mean value of the 1600x1800 central pixels of the product master bias.
- QC BIAS MASTER MEDIAN: Median value of the 1600x1800 central pixels of the product master bias.
- QC BIAS MASTER RMS: Population standard deviation of all the 1600x1800 central pixel values of the product master bias.
- QC BIAS MASTER NOISE: The expected noise is computed as the value of QC RON, divided by the square root of the number of raw bias frames used in the construction of the master bias. Next, the population standard deviation of the 1600x1800 central pixel values of the master bias is determined, excluding from the computation all values differing from QC BIAS MASTER MEDIAN more than three times the expected noise.
- QC BIAS MASTER FPN: The population standard deviation of the difference between the central 1600x1800 pixels of the master bias, and the region of the master bias shifted 10x10 pixels from the central one, is computed. This is the combination of fixed-pattern-noise and white noise (scaled by  $\sqrt{2}$ ). The white-noise contribution (QC BIAS MASTER NOISE) is then quadratically subtracted from the total noise.
- QC BIAS MASTER STRUCT: The population standard deviation of the 1600x1800 central pixels of the master bias is computed. This is the combination of structure, fixed-pattern-noise, and white-noise. The white-noise (QC BIAS MASTER NOISE) and the fixed-pattern-noise (QC BIAS MASTER FPN) contributions are then quadratically subtracted.

**KSigmaHigh:** Number of standard deviations above the median pixel value for rejecting a pixel value when *StackMethod* is set to "*Ksigma*".

**KSigmaLow:** Number of standard deviations below the median pixel value for rejecting a pixel value when *StackMethod* is set to “*Ksigma*”.

**MaxRejection:** Number of highest pixel values to be rejected when *StackMethod* is set to “*MinMax*”.

**MinRejection:** Number of lowest pixel values to be rejected when *StackMethod* is set to “*MinMax*”.

**RemoveOverscan:** When this parameter is set, the overscan regions are removed from the product master bias.

**StackMethod:** Combination method of input biases for master bias creation. See Section 9.6 for a complete description of all the combination methods. Possible settings are:

**Auto:** Given the number of input biases, an optimal bias combination method is selected. Currently this is always going to the method “*Average*”.

**Average:** The master bias is the mean of the input frames.

**Ksigma:** The master bias is the mean of the input frames, after K-sigma screening of pixel values. The number of sigma to be applied in the rejection is specified by the parameters *KSigmaLow* and *KSigmaHigh*.

**Median:** The master bias is the median of the input frames.

**MinMax:** The master bias is the mean of the input frames, after rejection of minimum and maximum values. The number of values to reject is specified by the parameters *MinRejection* and *MaxRejection*.

A description of the algorithms used in this recipe is given in Section 9.12, page 150.

### 7.3 vmdark

The VIMOS pipeline recipe *vmdark* is used to create a master dark frame from a set of raw dark frames. All the files that must be included in the input SOF are listed in Table 7.3.1.

DO category	Type	Explanation	Required
DARK	Raw frame	Dark exposure	✓
MASTER_BIAS	Calibration	Master bias	✓
CCD_TABLE	Calibration	Bad pixel table	

Table 7.3.1: *Input files for the vmdark recipe.*

A bad pixel table needs to be specified only if the cleaning of bad pixels is requested. In the calibration directories there is one CCD\_TABLE file for each quadrant, named *badpixel.q.tfits* (where *q* is the quadrant number in the case of imaging data, and the quadrant number increased by 4 in the case of spectral data). Care should be taken in selecting the appropriate bad pixel tables for imaging and spectral instrument modes.

The only product of the *vmdark* recipe is the master dark, as shown in Table 7.3.2.

The *vmdark* parameters are listed in Table 7.3.3.

A more complete description of the parameters meaning is also given:

File name	DO category	Type	Explanation
master_dark.fits	MASTER_DARK	FITS	Master dark

Table 7.3.2: *Product of the vmdark recipe.*

Parameter	Possible values	Explanation
AllowSingleFrames	true false	A single input dark is also allowed More than one input dark is required
StackMethod	Average Median MinMax Ksigma Auto	Master dark is average of input darks Master dark is median of input darks Master dark is obtained with min-max rejection Master dark is obtained with K-sigma clipping Optimal combination of input darks
MinRejection	<i>int</i>	No. of lowest rejected values for rejection method
MaxRejection	<i>int</i>	No. of highest rejected values for rejection method
KSigmaLow	<i>float</i> (sigma)	Low threshold for K-sigma clipping method
KSigmaHigh	<i>float</i> (sigma)	High threshold for K-sigma clipping method
BiasMethod	Master Zmaster	Bias removal with no overscan correction Bias removal with overscan correction
CleanBadPixel	true false	Interpolate bad pixels on master dark No bad pixel correction
CleanCosmic	true false	Remove cosmic ray events from each dark No cosmic ray removal
CosmicThreshold	<i>float</i>	Sigmas above level discriminator
CosmicRatio	<i>float</i>	Peak/neighbours discriminator
ComputeQC	true false	Compute QC parameters Do not compute QC parameters

Table 7.3.3: *vmdark parameters.*

**AllowSingleFrames:** If this parameter is set, then a master dark is produced also from a single input dark frame. In that case the *StackMethod* is ignored.

**BiasMethod:** Method for bias removal from the input dark frames. The bias removal procedure is described in some detail in Section 9.3. Possible settings are:

**Master:** After master bias subtraction, prescan and overscan regions are trimmed away from the dark frame.

**Zmaster:** After master bias subtraction the overscan correction is applied before trimming away the overscan regions.

**CleanBadPixel:** Bad pixel correction on the master dark. If this option is turned on, a bad pixel table should be specified in the input SOF (see Table 7.3.1). The bad pixel correction algorithm is described in Section 9.1, page 141.

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**CleanCosmic:** Cosmic ray events removal from each input dark. The cosmic ray rejection algorithm is described in Section 9.2, page 142.

**ComputeQC:** If this parameter is set, *Quality Control* (QC) parameters will be computed and written to the header of the output master dark and to an output QC PAF file named `qc0000.paf`. This file is not classified as a pipeline recipe product, as it is an intermediate dataset that in the standard pipeline operations would be translated into new entries in the QC log file. Currently the QC parameters computed by *vmdark* are:

QC DARK MASTER MEAN: Mean value of the 1600x1800 central pixels of the product master dark (ADU/s).

QC DARK MASTER RMS: Population standard deviation of all 1600x1800 central pixel values of the product master dark (ADU/s).

QC DARK MASTER MEDIAN: Median value of the 1600x1800 central pixels of the product master dark (ADU/s).

QC DARK CURRENT: Simple conversion of QC DARK MASTER MEDIAN into  $e^-/\text{pixel}/\text{hour}$ .

QC DARK CURRENT RMS: Simple conversion of QC DARK CURRENT RMS into  $e^-/\text{pixel}/\text{hour}$ .

**CosmicRatio:** Critical ratio for discriminating between objects and cosmic rays. This parameter is effective when *CleanCosmic* is set.

**CosmicThreshold:** Threshold for the selection of cosmic rays candidates. This parameter is effective when *CleanCosmic* is set.

**KSigmaLow:** Number of standard deviations below the median pixel value for rejecting a pixel value when *StackMethod* is set to “*Ksigma*”.

**KSigmaHigh:** Number of standard deviations above the median pixel value for rejecting a pixel value when *StackMethod* is set to “*Ksigma*”.

**MaxRejection:** Number of highest pixel values to be rejected when *StackMethod* is set to “*MinMax*”.

**MinRejection:** Number of lowest pixel values to be rejected when *StackMethod* is set to “*MinMax*”.

**StackMethod:** Combination method of input darks for master dark creation. See Section 9.6 for a complete description of all the combination methods. Possible settings are:

**Auto:** Given the number of input darks, an optimal dark combination method is selected. Currently this is always going to the method “*Average*”.

**Average:** The master dark is the mean of the input frames.

**Ksigma:** The master dark is the mean of the input frames, after K-sigma screening of pixel values. The number of sigma to be applied in the rejection is specified by the parameters *KSigmaLow* and *KSigmaHigh*.

**Median:** The master dark is the median of the input frames.

**MinMax:** The master dark is the mean of the input frames, after rejection of minimum and maximum values. The number of values to reject is specified by the parameters *MinRejection* and *MaxRejection*.

A description of the algorithms used in this recipe is given in Section 9.13, page 150.

## 7.4 vmimflatscreen

The VIMOS pipeline recipe *vmimflatscreen* is used to create a master screen flat field from a set of raw screen flat fields. The master screen flat field is not used directly in the flat field correction of scientific data, but it is optionally used just in the creation of a master sky flat field (see Section 7.5, page 72).

All the files that must be included in the input SOF are listed in table 7.4.1.

DO category	Type	Explanation	Required
IMG_SCREEN_FLAT	Raw frame	Screen flat field exposure	✓
MASTER_BIAS	Calibration	Master bias	✓
MASTER_DARK	Calibration	Master dark	
CCD_TABLE	Calibration	Bad pixel table	

Table 7.4.1: *Input files for the vmimflatscreen recipe.*

A bad pixel table needs to be specified only if the cleaning of bad pixels is requested. In the calibration directories there is one CCD\_TABLE file for each quadrant, named *badpixel.q.tfits* (where *q* is the quadrant number). Care should be taken in selecting the appropriate bad pixel tables for the imaging instrument mode (in the case of spectral data *q* is the quadrant number increased by 4).

The primary product of the *vmimflatscreen* recipe is the normalised master screen flat field, as shown in Table 7.4.2. A secondary product is the combined screen flat field, that is the result of the combination of all inputs but without any normalisation applied, and is just used for data quality control.

File name	DO category	Type	Explanation
img_master_screen_flat.fits	IMG_MASTER_SCREEN_FLAT	FITS	Master screen flat field
img_combined_screen_flat.fits	IMG_COMBINED_SCREEN_FLAT	FITS	Combined screen flat field

Table 7.4.2: *Products of the vmimflatscreen recipe.*

The *vmimflatscreen* parameters are listed in table 7.4.3.

A more complete description of the parameters meaning is also given:

**AllowSingleFrames:** If this parameter is set, then a master screen flat field is produced also from a single input screen flat field frame. In that case the *StackMethod* is ignored.

**BiasMethod:** Method for bias removal from the input screen flat field frames. The bias removal procedure is described in some detail in Section 9.3. Possible settings are:

**Master:** After master bias subtraction, prescan and overscan regions are trimmed away from the flat field frame.

**Zmaster:** After master bias subtraction the overscan correction is applied before trimming away the overscan regions.

Parameter	Possible values	Explanation
AllowSingleFrames	true false	A single input flat field is also allowed More than one input flat field is required
StackMethod	Average Median MinMax Ksigma Auto	Combined flat field is average of inputs Combined flat field is median of inputs Combined flat field is obtained with min-max rejection Combined flat field is obtained with K-sigma clipping Optimal combination of input flat fields
MinRejection	<i>int</i>	No. of lowest rejected values for rejection method
MaxRejection	<i>int</i>	No. of highest rejected values for rejection method
KSigmaLow	<i>float</i> (sigma)	Low threshold for K-sigma clipping method
KSigmaHigh	<i>float</i> (sigma)	High threshold for K-sigma clipping method
BiasMethod	Master Zmaster	Bias removal with no overscan correction Bias removal with overscan correction
CleanBadPixel	true false	Interpolate bad pixels on product flat fields No bad pixel correction
CleanCosmic	true false	Remove cosmic ray events from each flat field No cosmic ray removal
CosmicThreshold	<i>float</i>	Sigmas above level discriminator
CosmicRatio	<i>float</i>	Peak/neighbours discriminator
SmoothBoxSize	<i>int</i> (pixel)	Size of smoothing running box
SmoothMethod	Median Average	Median of values in running box Average of values in running box
ComputeQC	true false	Compute QC parameters Do not compute QC parameters

Table 7.4.3: *vmimflatscreen* parameters.

**CleanBadPixel:** Bad pixel correction on the products. If this option is turned on, a bad pixel table should be specified in the input SOF (see Table 7.5.1). The bad pixel correction algorithm is described in Section 9.1, page 141.

**CleanCosmic:** Cosmic ray events removal from each input flat field. The cosmic ray rejection algorithm is described in Section 9.2, page 142.

**ComputeQC:** If this parameter is set, *Quality Control* (QC) parameters will be computed and written to the header of the output master screen flat field and to an output QC PAF file named `qc0000.paf`. This file is not classified as a pipeline recipe product, as it is an intermediate dataset that in the standard pipeline operations would be translated into new entries in the QC log file. The QC parameters are computed only if the exposure time of the first two raw screen flat fields listed in the input SOF is the same (within 4%). Currently the QC parameters computed by *vmimflatscreen* are:

QC CONAD: Conversion factor from ADU to electrons ( $e^-/\text{ADU}$ ). The difference frame of the first two raw screen flat fields listed in the input SOF is computed. Then the 1600x1800 central region of the image is divided into 16x18 100x100 boxes. For each one of these boxes, the median signal level

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from the first raw frame is divided by the variance in the difference frame scaled by 2. The median value of the 16x18 values obtained is the accepted value for the gain conversion factor.

QC CONAD RMS: The rms of the 16x18 values obtained in the determination of QC CONAD is computed, and divided by the square root of 16x18.

QC FLAT PHN: Photon noise (in ADU). The standard deviation of the 1600x1800 pixel central region of the difference of the first two raw screen flat fields listed in the input SOF is computed and then scaled by  $\sqrt{2}$ .

QC FLAT FPN: Fixed pattern noise (in ADU). The difference between the 1600x1800 central pixels of the first frame, and the same region shifted by 10x10 pixels in the second frame, is computed. The standard deviation of the signal is the combination of fixed pattern noise and photon noise (scaled by  $\sqrt{2}$ ). The photon noise QC FLAT PHN is then quadratically subtracted.

QC FLAT STRUCT: Screen flat field structure (in ADU). The population standard deviation of the 1600x1800 central pixels of the first flat field in the input SOF is computed. This is the combination of structure, fixed pattern noise QC FLAT FPN, and photon noise QC FLAT PHN. The photon noise and the fixed pattern noise are then quadratically subtracted.

QC FLAT EFFICIENCY: Signal per unit of exposure (in ADU/s). The median level of the 1600x1800 central pixels of the first input screen flat field is divided by its exposure time.

QC FLAT MASTER MEDIAN: Median value of the 1600x1800 central pixels of the combined screen flat field.

QC FLAT MASTER RMS: Population standard deviation of the 1600x1800 central pixels of the combined screen flat field.

**CosmicRatio:** Critical ratio for reducing the effect of variable background on cosmic rays identification. This parameter is effective when *CleanCosmic* is set.

**CosmicThreshold:** Threshold for the selection of cosmic rays candidates. This parameter is effective when *CleanCosmic* is set.

**KSigmaHigh:** Number of standard deviations above the median pixel value for rejecting a pixel value when *StackMethod* is set to "*Ksigma*".

**KSigmaLow:** Number of standard deviations below the median pixel value for rejecting a pixel value when *StackMethod* is set to "*Ksigma*".

**MaxRejection:** Number of highest pixel values to be rejected when *StackMethod* is set to "*MinMax*".

**MinRejection:** Number of lowest pixel values to be rejected when *StackMethod* is set to "*MinMax*".

**SmoothBoxSize:** Length in pixel of the side of the square smoothing box used in the normalisation of the master flat field.

**SmoothMethod:** The smoothing method used in the normalisation of the master flat field. Possible settings are:

**Average:** The central pixel within the smoothing running box is replaced with the average of the values of the pixels contained in the box.

**Median:** The central pixel within the smoothing running box is replaced with the median of the values of the pixels contained in the box.

**StackMethod:** Combination method of input screen flat fields for combined flat field creation. See Section 9.6 for a complete description of all the combination methods. Possible settings are:

**Auto:** Given the number of input screen flat fields, an optimal combination method is selected. Currently this is always going to the method “Average”.

**Average:** The combined screen flat field is the mean of the input frames.

**Ksigma:** The combined screen flat field is the mean of the input frames, after K-sigma screening of pixel values. The number of sigma to be applied in the rejection is specified by the parameters *KSigmaLow* and *KSigmaHigh*.

**Median:** The combined screen flat field is the median of the input frames.

**MinMax:** The combined screen flat field is the mean of the input frames, after rejection of minimum and maximum values. The number of values to reject is specified by the parameters *MinRejection* and *MaxRejection*.

A description of the algorithms used in this recipe is given in Section 9.14, page 151.

## 7.5 vmimflatsky

The VIMOS pipeline recipe *vmimflatsky* is used to create a master sky flat field from a set of raw sky flat fields. The master sky flat field is the dataset used for the flat field correction of scientific data.

All the files that must be included in the input SOF are listed in table 7.5.1.

DO category	Type	Explanation	Required
IMG_SKY_FLAT	Raw frame	Sky flat field exposure	✓
MASTER_BIAS	Calibration	Master bias	✓
MASTER_DARK	Calibration	Master dark	
IMG_MASTER_SCREEN_FLAT	Calibration	Master screen flat field	
CCD_TABLE	Calibration	Bad pixel table	

Table 7.5.1: *Input files for the vmimflatsky recipe.*

A bad pixel table needs to be specified only if the cleaning of bad pixels is requested. In the calibration directories there is one CCD\_TABLE file for each quadrant, named *badpixel.q.tfits* (where *q* is the quadrant number). Care should be taken in selecting the appropriate bad pixel tables for the imaging instrument mode (in the case of spectral data *q* is the quadrant number increased by 4).

The only product of the *vmimflatsky* recipe is the normalised master sky flat field, as shown in Table 7.5.2.

The *vmimflatsky* parameters are listed in table 7.5.3.

A more complete description of the parameters meaning is also given:



File name	DO category	Type	Explanation
img_master_sky_flat.fits	IMG_MASTER_SKY_FLAT	FITS	Master sky flat field

Table 7.5.2: *Products of the vmimflatsky recipe.*

**AllowSingleFrames:** If this parameter is set, then a master sky flat field is produced also from a single input sky flat field frame. In that case the *StackMethod* is ignored.

**BiasMethod:** Method for bias removal from the input sky flat field frames. The bias removal procedure is described in some detail in Section 9.3. Possible settings are:

**Master:** After master bias subtraction, prescan and overscan regions are trimmed away from the flat field frame.

**Zmaster:** After master bias subtraction the overscan correction is applied before trimming away the overscan regions.

**CleanBadPixel:** Bad pixel correction on the master sky flat field. If this option is turned on, a bad pixel table should be specified in the input SOF (see Table 7.5.1). The bad pixel correction algorithm is described in Section 9.1, page 141.

**CleanCosmic:** Cosmic ray events removal from each input flat field. The cosmic ray rejection algorithm is described in Section 9.2, page 142.

**ComputeQC:** If this parameter is set, *Quality Control* (QC) parameters will be computed and written to the header of the output master sky flat field and to an output QC PAF file named `qc0000.paf`. This file is not classified as a pipeline recipe product, as it is an intermediate dataset that in the standard pipeline operations would be translated into new entries in the QC log file. Currently the QC parameters computed by *vmimflatsky* are:

QC SKY FLAT FLUX: Mean value of the 1600x1800 central pixels of the first sky flat field listed in the input SOF, after bias removal and division by the exposure time.

QC SKY FLAT RMS: The population standard deviation of the 1600x1800 central pixels of the normalised master sky flat field.

QC SKY FLAT STRUCT: The standard deviation QC SKY FLAT RMS can be seen as the combination of large scale structure with noise sources. The difference between the master and the master itself shifted by 10x10 pixels is computed, and the variance of the 1600x1800 central pixels of the result is computed and corrected by a factor 2. This evaluation of other noise sources is then quadratically subtracted from the total standard deviation.

**CosmicRatio:** Critical ratio for reducing the effect of variable background on cosmic rays identification. This parameter is effective when *CleanCosmic* is set.

**CosmicThreshold:** Threshold for the selection of cosmic rays candidates. This parameter is effective when *CleanCosmic* is set.

**KSigmaHigh:** Number of standard deviations above the median pixel value for rejecting a pixel value when *StackMethod* is set to “*Ksigma*”.

Parameter	Possible values	Explanation
AllowSingleFrames	true false	A single input flat field is also allowed More than one input flat field is required
StackMethod	Average Median MinMax Ksigma Auto	Combined flat field is average of inputs Combined flat field is median of inputs Combined flat field is obtained with min-max rejection Combined flat field is obtained with K-sigma clipping Optimal combination of input flat fields
MinRejection	<i>int</i>	No. of lowest rejected values for rejection method
MaxRejection	<i>int</i>	No. of highest rejected values for rejection method
KSigmaLow	<i>float</i> (sigma)	Low threshold for K-sigma clipping method
KSigmaHigh	<i>float</i> (sigma)	High threshold for K-sigma clipping method
BiasMethod	Master Zmaster	Bias removal with no overscan correction Bias removal with overscan correction
CleanBadPixel	true false	Interpolate bad pixels on master sky flat No bad pixel correction
CleanCosmic	true false	Remove cosmic ray events from each flat field No cosmic ray removal
CosmicThreshold	<i>float</i>	Sigmas above level discriminator
CosmicRatio	<i>float</i>	Peak/neighbours discriminator
SmoothBoxSize	<i>int</i> (pixel)	Size of smoothing running box
SmoothMethod	Median Average	Median of values in running box Average of values in running box
ComputeQC	true false	Compute QC parameters Do not compute QC parameters

Table 7.5.3: *vmimflatsky* parameters.

**KSigmaLow:** Number of standard deviations below the median pixel value for rejecting a pixel value when *StackMethod* is set to “*Ksigma*”.

**MaxRejection:** Number of highest pixel values to be rejected when *StackMethod* is set to “*MinMax*”.

**MinRejection:** Number of lowest pixel values to be rejected when *StackMethod* is set to “*MinMax*”.

**SmoothBoxSize:** Length in pixel of the side of the square smoothing box used in the normalisation of the master flat field.

**SmoothMethod:** The smoothing method used in the normalisation of the master flat field. Possible settings are:

**Median:** The central pixel within the smoothing running box is replaced with the median of the values of the pixels contained in the box.

**Average:** The central pixel within the smoothing running box is replaced with the average of the values of the pixels contained in the box.

**StackMethod:** Combination method of input sky flat fields for combined flat field creation. See Section 9.6 for a complete description of all the combination methods. Possible settings are:

**Auto:** Given the number of input sky flat fields, an optimal combination method is selected. Currently this is always going to the method “Average”.

**Average:** The combined sky flat field is the mean of the input frames.

**Ksigma:** The combined sky flat field is the mean of the input frames, after K-sigma screening of pixel values. The number of sigma to be applied in the rejection is specified by the parameters *KSigmaLow* and *KSigmaHigh*.

**Median:** The combined sky flat field is the median of the input frames.

**MinMax:** The combined sky flat field is the mean of the input frames, after rejection of minimum and maximum values. The number of values to reject is specified by the parameters *MinRejection* and *MaxRejection*.

A description of the algorithms used in this recipe is given in Section 9.15, page 151.

## 7.6 vmmasktoccd

The VIMOS pipeline recipe *vmmasktoccd* is used to determine the CCD to Mask transformation and its inverse (see Section 8.2.1, page 133). SExtractor v2.1.6 [8] is used for determining the positions of the spotlights on a direct imaging exposure of a lamp and a calibration mask containing a regular grid of pinholes. The relation between mask and CCD positions is then determined.<sup>9</sup>

The files to be included in the input SOF are listed in Table 7.6.1.

DO category	Type	Explanation	Required
MASK_TO_CCD	Raw frame	Pinhole mask exposure	✓
MASTER_BIAS	Calibration	Master bias	✓
MASTER_DARK	Calibration	Master dark	
IMG_MASTER_SKY_FLAT	Calibration	Master flat field	
CCD_TABLE	Calibration	Bad pixel table	

Table 7.6.1: *Input files for the vmmasktoccd recipe.*

A bad pixel table needs to be specified only if the cleaning of bad pixels is requested. In the calibration directories there is one CCD\_TABLE file for each quadrant, named *badpixel.q.tfits* (where *q* is the quadrant number). Care should be taken in selecting the appropriate bad pixel tables for the imaging instrument mode (in the case of spectral data *q* is the quadrant number increased by 4).

The only product of the *vmmasktoccd* recipe is shown in Table 7.6.2. This PAF file is copied (or moved) to the product directory, and it is identical to the produced *Instrument WorkStation* (IWS) configuration file *IMG\_mask2ccd\_q.cmf* (where *q* indicates the VIMOS quadrant number) that is created in the same directory where the recipe is launched.

<sup>9</sup>The *vmmasktoccd* recipe is not distributed outside ESO because of licensing problems.

File name	DO category	Type	Explanation
IMG_mask2ccd_q.paf		PAF	Mask to CCD configuration file

Table 7.6.2: *Products of the vmmasktoccd recipe.*

The transformation and distortion models related to the CCD and the mask focal planes are described in Section 8.2.1, page 133. Typically, the RMS of the CCD to mask model residuals is about  $5 \cdot 10^{-3}$  mm, while the RMS of the inverse transformation is about 0.04 pixel (being related through the 8.4 mm/pixel scale factor). Of course the real accuracy of the model may be better than that, considering that about 500 pinholes positions are fitted to determine the transformations: if the distribution of the residuals were poissonian, the model accuracy would be more accurate than the residuals population RMS by a factor of the order of  $\sqrt{500/22} \simeq 5$  (where 22 is the number of the model's free parameters).

The *vmmasktoccd* parameters are listed in Table 7.6.3.

Parameter	Possible values	Explanation
BiasMethod	Master Zmaster	Bias removal with no overscan correction Bias removal with overscan correction
CleanBadPixel	true false	Clean bad pixels Do not clean bad pixels
CleanCosmic	true false	Clean cosmic rays Do not clean cosmic rays
CosmicThreshold	<i>float</i>	Sigmas above level discriminator
CosmicRatio	<i>float</i>	Peak/neighbours discriminator
Iterations	<i>int</i>	Number of model iterations
PolyOrderX	<i>int</i>	Order of the <i>x</i> distortion model
PolyOrderY	<i>int</i>	Order of the <i>y</i> distortion model
SearchRadius	<i>float</i> (pixel)	Max distance from expected positions
SExtractor.FilterName	<i>file</i>	SExtractor convolution mask
SExtractor.HolesParam	<i>file</i>	SExtractor output parameters
SExtractor.HolesSex	<i>file</i>	SExtractor configuration file
SExtractor.PsfEx	<i>file</i>	PSF modeling executable
SExtractor.PsfexDefault	<i>file</i>	PSF modeling configuration file
SExtractor.PsfParam	<i>file</i>	SExtractor output parameters for PSF modeling
SExtractor.PsfSex	<i>file</i>	SExtractor configuration file used for PSF modeling
SExtractor.SExtractor	<i>file</i>	SExtractor executable
SExtractor.StarNnwName	<i>file</i>	SExtractor neural network weights

Table 7.6.3: *vmmasktoccd parameters.*

A more complete description of the parameters meaning is also given:

**BiasMethod:** Method for bias removal from the pinhole mask image. The bias removal procedure is described in some detail in Section 9.3. Possible settings are:

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**Master:** After master bias subtraction, prescan and overscan regions are trimmed away from the pinhole mask image.

**Zmaster:** After master bias subtraction the overscan correction is applied before trimming away the overscan regions.

**CleanBadPixel:** Bad pixel correction on the pinhole mask image. If this option is turned on, a bad pixel table should be specified in the input SOF (see Table 7.6.1). The bad pixel correction algorithm is described in Section 9.1, page 141.

**CleanCosmic:** Cosmic ray events removal from pinhole mask image. The cosmic ray rejection algorithm is described in Section 9.2, page 142.

**CosmicRatio:** Critical ratio for discriminating between objects and cosmic rays. This parameter is effective when *CleanCosmic* is set.

**CosmicThreshold:** Threshold for the selection of cosmic rays candidates. This parameter is effective when *CleanCosmic* is set.

**Iterations:** Max number of iterations of the distortion model fit.

**PolyOrderX:** Order of the bivariate polynomial for the  $x$  coordinate distortion. Note that VMMPS requires this to be set to 3.

**PolyOrderY:** Order of the bivariate polynomial for the  $y$  coordinate transformation. Note that VMMPS requires this to be set to 3.

**SearchRadius:** Max distance (in pixels) from expected position where a pinhole is searched.

The parameters belonging to the SExtractor group should not be modified.

A description of the algorithms used in this recipe is given in Section 9.16, page 153.

## 7.7 vmskyccd

The VIMOS pipeline recipe *vmskyccd* is used to determine the CCD to Sky distortion and its inverse (see Section 8.2.2, page 134). SExtractor v2.1.6 [8] is used for detecting in the field-of-view the objects matching the entries of an astrometric catalog. The deviations from the theoretical relation between CCD and celestial coordinates (WCS) are then determined and modeled.<sup>10</sup>

The files to be included in the input SOF are listed in Table 7.7.1.

A bad pixel table needs to be specified only if the cleaning of bad pixels is requested, and the photometric table is required only if star matching is based also on comparing the measured and the catalog magnitudes.

In the calibration directories there is one `CCD_TABLE` file for each quadrant, named `badpixel.q.tfits` (where  $q$  is the quadrant number). Care should be taken in selecting the appropriate bad pixel tables for the imaging instrument mode (in the case of spectral data  $q$  is the quadrant number increased by 4).

<sup>10</sup>The *vmskyccd* recipe is not distributed outside ESO.

DO category	Type	Explanation	Required
IMG_Astrometry	Raw frame	Astrometric field exposure	✓
MASTER_BIAS	Calibration	Master bias	✓
MASTER_DARK	Calibration	Master dark	
IMG_MASTER_SKY_FLAT	Calibration	Master flat field	✓
ASTROMETRIC_TABLE	Calibration	Astrometric catalog	✓
PHOTOMETRIC_TABLE	Calibration	Photometric table	
CCD_TABLE	Calibration	Bad pixel table	

Table 7.7.1: *Input files for the vmskyccd recipe.*

The standard photometric tables in the calibration directories are named `ipc_f.q.tfits` (where *f* is the filter name and *q* the quadrant number), while the astrometric catalogue is contained in tables `regionx.tfits` (where *x* is a character between A and P). The name of the table to be used to process a given exposure can be derived from the value of its FITS header keyword `ESO OBS TARG NAME`.

The products of the *vmskyccd* recipe are shown in Table 7.7.2.

File name	DO category	Type	Explanation
IMG_sky2ccd_q.paf		PAF	Sky to CCD configuration file
img_astrometry_reduced.fits	IMG_Astrometry_REDUCED	FITS	Reduce astrometric field exposure

Table 7.7.2: *Products of the vmskyccd recipe.*

The PAF file is copied (or moved) to the product directory, and is identical to the *Instrument WorkStation* (IWS) configuration file `IMG_sky2ccd_q.cmfi` (where *q* indicates the VIMOS quadrant number) that is created in the same directory where the recipe is launched.

The reduced astrometric image is a byproduct of the distortions modeling, and can be used to ensure that the data are suitable for the purpose. Quality indicators as the *seeing* are not critical in this context, but the number and the distribution of the identified astrometric stars in the field-of-view is of fundamental importance for a realistic modeling of the distortions through polynomial fitting. This, together with the RMS of the model residuals (see Section 8.2.2, page 134), should make possible to discriminate between a safe and an unsafe modeling of the sky to CCD distortions.

The *vmskyccd* parameters are listed in Table 7.7.3.

Only few parameters of the SExtractor group are listed here: almost all the entries of the SExtractor configuration file, `$PIPE_HOME/vimos/config/vimos.sex`, can be overruled by the SExtractor group parameter values specified in the *vmskyccd.rc* configuration file. Conventionally, a SExtractor configuration parameter name matches the *vmskyccd* configuration parameter obtained by lowercasing all of its characters with the exception of the first character of each word, and removing the underscore. For instance, the SExtractor parameter `CATALOG_TYPE` matches the *vmskyccd* parameter *CatalogType*. When using the corresponding command line option, the SExtractor group must be explicitly specified. For instance, the command option corresponding to the parameter *CatalogType* is `--SExtractor.CatalogType`.

The *Window* parameter has no counterpart in the SExtractor configuration file, and is used to restrict the

Parameter	Possible values	Explanation
ApplyZeropoint	true false	Apply zeropoint correction Do not apply zeropoint correction
BiasMethod	Master Zmaster	Bias removal with no overscan correction Bias removal with overscan correction
CleanBadPixel	true false	Clean bad pixels Do not clean bad pixels
CleanCosmic	true false	Clean cosmic rays Do not clean cosmic rays
CosmicThreshold	<i>float</i>	Sigmas above level discriminator
CosmicRatio	<i>float</i>	Peak/neighbours discriminator
KSigmaClip	<i>float</i>	Sigma clipping threshold used in star match
MagFinal	<i>float</i>	Magnitude tolerance for final star match
MagInitial	<i>float</i>	Magnitude tolerance for initial star match
MagLimit	<i>float</i>	Max magnitude for object selection
RemoteCatalog	true false	<i>Not yet implemented</i> No online access to a catalog server
SearchRadius	<i>float</i> (")	Max distance for star matching
StarIndex	<i>float</i>	Min stellarity index for stars selection
TemperatureCheck	true false	Check beam and ambient temperatures consistency Do not check consistency of temperatures
TemperatureTolerance	<i>float</i> ( $^{\circ}C$ )	Max difference beam - ambient temperatures
SExtractor.FilterName	<i>file</i>	SExtractor convolution mask
SExtractor.SExtractor	<i>file</i>	SExtractor executable
SExtractor.StarNnwName	<i>file</i>	SExtractor neural network weights
SExtractor.Window	<i>file</i>	Image region where SExtractor is applied

Table 7.7.3: *vmskyccd* parameters.

SExtractor operations to just a part of the input image. This is useful to avoid false detections along the vignettted image region.

A more complete description of the parameters not belonging to the SExtractor group is given here:

**ApplyZeropoint:** If this parameter is set, a photometric table must be specified in the input SOF, and the magnitude zeropoint, the extinction coefficient, and the colour term (with the colour it refers to) are copied from the photometric table to the reduced astrometric image header. If this parameter is set to false, the parameters *MagInitial* and *MagFinal* are ignored.

**BiasMethod:** Method for bias removal from the astrometric image. The bias removal procedure is described in some detail in Section 9.3. Possible settings are:

**Master:** After master bias subtraction, prescan and overscan regions are trimmed away from the astrometric image.

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**Zmaster:** After master bias subtraction the overscan correction is applied before trimming away the overscan regions.

**CleanBadPixel:** Bad pixel correction on the astrometric image. If this option is turned on, a bad pixel table should be specified in the input SOF (see Table 7.7.1). The bad pixel correction algorithm is described in Section 9.1, page 141.

**CleanCosmic:** Cosmic ray events removal from astrometric image. The cosmic ray rejection algorithm is described in Section 9.2, page 142.

**CosmicThreshold:** Threshold for the selection of cosmic rays candidates. This parameter is effective when *CleanCosmic* is set.

**CosmicRatio:** Critical ratio for discriminating between objects and cosmic rays. This parameter is effective when *CleanCosmic* is set.

**KSigmaClip:** Number of sigmas used in the spatial rejection of matched stars. Stars found within the specified *SearchRadius* are compared to their expected catalog positions, and the sigma of the residuals distribution is computed. Then, all the stars having a distance from the expected position greater than the specified threshold are rejected.

**MagFinal:** Magnitude tolerance applied to matched stars, after the K-sigma clipping has been applied. The stars magnitudes should not differ from the corresponding catalog magnitudes more than this value.

**MagInitial:** Magnitude tolerance applied in star matching.

**MagLimit:** Limiting magnitude of objects to be matched with the astrometric stars from the input catalog.

**SearchRadius:** Max distance (in arcseconds) from the expected position of a catalog star.

**StarIndex:** This index can have a value between 0 (minimal stellarity) and 1 (maximal stellarity). Only the identified objects having a stellarity index greater than the specified value will be taken as stars, to be matched with the standard stars from the input catalog.

**TemperatureCheck:** For associating the detected stars with the reference catalog, their coordinates must be corrected applying a “first guess” CCD to Sky distortion corrected for changes in the beam temperature (see Sections 8.2.2 and 9.17). If this parameter is set, the beam temperature is compared with the temperatures of the other beams and with the ambient temperature. If the difference between the beam temperature and the ambient temperature is greater than the threshold specified by *TemperatureTolerance*, then the temperature used will be the mean of the beams temperatures that differ from the ambient temperature less than the specified threshold. If not a single beam temperature is within tolerance, then the ambient temperature is used in place of the beam temperature. This option was just introduced to prevent possible problems with the beam temperature sensors.

**TemperatureTolerance:** Max tolerated difference between ambient and beam temperatures. This parameter is effective only if *TemperatureCheck* is set.

The order of the polynomials used in the distortions modeling is taken from the “first guess” model found in the input astrometric image header (see Table 8.2.3, page 135).



In the directory `$PIPE_HOME/vimos/ima/cal` is located the astrometric catalog currently used by *vmiskyccd* (see reference [11]). The catalog is split into a number of tables named `regionA.tfits`, `regionB.tfits`, ..., `regionP.tfits`. The table indicated in the SOF should match the content of the header entry `ESO OBS TARG NAME` of the input astrometric image.

It should be noted that in this astrometric catalog just the R band magnitudes are given, therefore astrometric fields exposures should always be made with the R filter.

A description of the algorithms used in this recipe is given in Section 9.16, page 153.

## 7.8 vmimstandard

The VIMOS pipeline recipe *vmimstandard* is used to determine the instrumental magnitude of the stars matching the entries of a photometric catalog. SExtractor v2.1.6 [8] is used for the source detection task.

The files to be included in the input SOF are listed in Table 7.8.1.

DO category	Type	Explanation	Required
IMG_STANDARD	Raw frame	Standard stars field	✓
IMG_MASTER_SKY_FLAT	Calibration	Master sky flat field	✓
MASTER_BIAS	Calibration	Master bias	✓
MASTER_DARK	Calibration	Master dark	
PHOTOMETRIC_CATALOG	Calibration	Photometric catalog	✓
CCD_TABLE	Calibration	Bad pixel table	
PHOTOMETRIC_TABLE	Calibration	Photometric table	

Table 7.8.1: Input files for the *vmimstandard* recipe.

The bad pixel table needs to be specified only if the cleaning of bad pixels is requested. In the calibration directories there is one `CCD_TABLE` file for each quadrant, named `badpixel.q.tfits` (where *q* is the quadrant number). Care should be taken in selecting the appropriate bad pixel tables for the imaging instrument mode (in the case of spectral data *q* is the quadrant number increased by 4).

The optional determination of the frame magnitude zeropoint from the table of detected standard stars (see ahead) would require to specify in the input SOF a photometric table. The photometric table simply holds the necessary parameters for the magnitude zeropoint computation, as listed in Table 7.8.2. The standard photometric tables in the calibration directories are named `ipc_f.q.tfits` (where *f* is the filter name and *q* the quadrant number).

The photometric catalog currently used can be found in the directory `$PIPE_HOME/vimos/ima/cal`, in the file `phstd_stetson.tfits` (see Table 7.8.3). This table includes the photometric stars from the Stetson's fields (see <http://cadwww.dao.nrc.ca/standards>); Landolt's stars (Landolt 1992, AJ 104, 340) that can be found in the Stetson's fields are also included, to permit the determination of zeropoints also in the U band.

The products of the *vmimstandard* recipe are shown in Table 7.8.4.

The galaxy table is the output of SExtractor [8] converted into FITS format (see Table 7.11.3, page 91). The star

Keyword	Example	Explanation
PRO MAG ZERO	28.15	Expected magnitude zeropoint
PRO EXTINGT	0.25	Atmospheric extinction coefficient
PRO COLTERM	0.01	Correction for star colour
PRO COLOUR	'B-V'	Colour system used
PRO MAGZERO RMS	0.05	Error on expected zeropoint
PRO EXTINGT RMS	0.00	Error on extinction coefficient
PRO COLTERM RMS	0.00	Error on colour term

Table 7.8.2: *Photometric table entries.*

Column name	Explanation
ID	Star identification string
RA	RA of star
DEC	Dec of star
MAG_U	U magnitude of star
MAG_B	B magnitude of star
MAG_V	V magnitude of star
MAG_R	R magnitude of star
MAG_I	I magnitude of star

Table 7.8.3: *Photometric catalog entries.*

match table is the list of identified standard stars, with their positions on sky and CCD and their instrumental and catalog magnitudes, as shown in Table 7.8.5.

The same procedure applied by the recipe *vmimobsstare* (see Section 7.11, page 89) is used to reduce the standard field image. The reduced image is a byproduct of the star matching task, and can be used for quality control purposes.

The *vmimstandard* parameters are listed in Table 7.8.6.

Only few parameters of the SExtractor group are listed here: almost all the entries of the SExtractor configuration file, `$PIPE_HOME/vimos/config/vimos.sex`, can be overruled by the SExtractor group parameter values specified in the *vmimstandard.rc* configuration file. Conventionally, a SExtractor configuration parameter name matches the *vmimstandard* configuration parameter obtained by lowercasing all of its characters with the exception of the first character of each word, and removing the underscore. For instance, the SExtractor parameter `CATALOG_TYPE` matches the *vmimstandard* parameter *CatalogType*. When using the corresponding command line option, the SExtractor group must be explicitly specified. For instance, the command option corresponding to the parameter *CatalogType* is `--SExtractor.CatalogType`.

The *Window* parameter has no counterpart in the SExtractor configuration file, and is used to restrict the SExtractor operations to just a part of the input image. This is useful to avoid false detections along the vignettted image region.

A more complete description of the parameters not belonging to the SExtractor group is given here:

File name	DO category	Type	Explanation
img_star_match_table.fits	IMG_STAR_MATCH_TABLE	FITS	List of identified standard stars
img_standard_reduced.fits	IMG_STANDARD_REDUCED	FITS	Reduced standard stars field
img_galaxy_table.fits	IMG_GALAXY_TABLE	FITS	List of detected objects

Table 7.8.4: *Products of the vmimstandard recipe.*

Column name	Explanation
NUMBER	Object number in SExtractor output (galaxy table)
ID	Star identification string, from input catalog
X_IMAGE	X image pixel position of matched star (SExtractor)
Y_IMAGE	Y image pixel position of matched star (SExtractor)
X_WORLD	RA of matched star (SExtractor)
Y_WORLD	Dec of matched star (SExtractor)
MAG	Instrumental magnitude (SExtractor)
RA	Catalog RA of matched star
DEC	Catalog Dec of matched star
MAG_U	Catalog U magnitude of matched star
MAG_B	Catalog B magnitude of matched star
MAG_V	Catalog V magnitude of matched star
MAG_R	Catalog R magnitude of matched star
MAG_I	Catalog I magnitude of matched star

Table 7.8.5: *Star match table entries.*

**BiasMethod:** Method for bias removal from the input standard stars field exposures. The bias removal procedure is described in some detail in Section 9.3. Possible settings are:

**Master:** After master bias subtraction, prescan and overscan regions are trimmed away from the standard stars field frame.

**Zmaster:** After master bias subtraction the overscan correction is applied before trimming away the overscan regions.

**CleanBadPixel:** Bad pixel correction on the reduced standard stars field exposure. If this option is turned on, a bad pixel table should be specified in the input SOF (see Table 7.8.1). The bad pixel correction algorithm is described in Section 9.1, page 141.

**CleanCosmic:** Cosmic ray events removal from input standard stars field exposure. The cosmic ray rejection algorithm is described in Section 9.2, page 142.

**ComputeQC:** If this parameter is set, *Quality Control* (QC) parameters will be computed and written partly to the header of the output galaxy table and partly to the header of the reduced standard field frame (depending on the dataset used for their computation). They will also be written to two output QC PAF files named `qc0000.paf` and `qc0001.paf`. These files are not classified as pipeline recipe products, as they are intermediate datasets that in the standard pipeline operations would be translated into new

Parameter	Possible values	Explanation
BiasMethod	Master Zmaster	Bias removal with no overscan correction Bias removal with overscan correction
CleanBadPixel	true false	Clean bad pixels Do not clean bad pixels
CleanCosmic	true false	Clean cosmic rays Do not clean cosmic rays
CosmicThreshold	<i>float</i>	Sigmas above level discriminator
CosmicRatio	<i>float</i>	Peak/neighbours discriminator
ComputeQC	true false	Compute QC parameters Do not compute QC parameters
MagLimit	<i>float</i>	Max magnitude for star selection
StarIndex	<i>float</i>	Index used for star/galaxy discrimination
SearchRadius	<i>float</i> (arcsec)	Search radius used in stars identification
KSigmaClip	<i>float</i> (sigma)	Sigma clipping factor used in star matching
MagInitial	<i>float</i>	Magnitude tolerance for initial stars selection
MagFinal	<i>float</i>	Magnitude tolerance for final stars selection
MinStars	<i>int</i>	Minimum number of matching stars required
TemperatureCheck	true false	Check beam and ambient temperatures consistency Do not check consistency of temperatures
TemperatureTolerance	<i>float</i> ( $^{\circ}C$ )	Max difference beam - ambient temperatures
ReduceAnyFrame	true false	Any input image is reduced Reduce only if pointing to standard stars field
SExtractor.FilterName	<i>file</i>	SExtractor convolution mask
SExtractor.SExtractor	<i>file</i>	SExtractor executable
SExtractor.StarNnwName	<i>file</i>	SExtractor neural network weights
SExtractor.Window	<i>file</i>	Image region where SExtractor is applied

Table 7.8.6: *vmimstandard* parameters.

entries in the QC log file. The QC parameters computed by *vmimstandard* are the same that are computed by the pipeline recipe *vmimobsstare* (see Section 7.11, page 89), with some extra ones that are all written to the header of the reduced standard stars field image, and to the file `qc0001.paf`:

QC ZEROPOINT NSTARS: Number of stars used in the frame zeropoint computation.

QC ZEROPOINT: Gain corrected frame zeropoint. This is computed as a robust estimate of the values  $Z_i$  obtained for all the identified standard stars:

$$Z_i = \Delta M_i + E \cdot A + C \cdot C_i$$

where, for a given star  $i$ ,  $\Delta M_i$  is the observed difference between the catalog magnitude and the instrumental magnitude in the appropriate band,  $C_i$  is the known colour index,  $A$  is the airmass, read from the keyword `PRO AIRMASS` of the input frame header,  $E$  is the atmospheric extinction coefficient at the considered band, read from the photometric table (see Table 7.8.2), and  $C$  is the colour term. The estimate  $Z$  is computed using a biweight estimator function taken from the Rostat

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program written by T.Beers for robust statistics on a data set (see Beers, Flynn, Gebhardt 1990, AJ 100, 32). This estimate is then corrected for the instrument gain:

$$Z_g = Z + 2.5 \log_{10} g$$

where  $g$  is the CCD gain factor in  $e^-/\text{ADU}$ . The  $Z$  frame zeropoint, not normalised to the gain factor and more useful for data analysis purposes, is saved to the header of the reduced frame at the keyword PRO MAG ZERO, together with its error PRO MAGZERO RMS.

QC ZEROPOINT RMS : Error on gain corrected frame zeropoint as obtained from the biweight estimator function.

**CosmicRatio:** Critical ratio for discriminating between objects and cosmic rays. This parameter is effective when *CleanCosmic* is set.

**CosmicThreshold:** Threshold for the selection of cosmic rays candidates. This parameter is effective when *CleanCosmic* is set.

**KSigmaClip:** Number of sigmas used in the spatial rejection of matched stars. Stars found within the specified *SearchRadius* are compared to their expected catalog positions, and the sigma of the residuals distribution is computed. Then, all the stars having a distance from the expected position greater than the specified threshold are rejected.

**MagFinal:** Magnitude tolerance applied to matched stars, after the K-sigma clipping has been applied. The stars magnitudes should not differ from the corresponding catalog magnitudes more than this value.

**MagInitial:** Magnitude tolerance applied in star matching.

**MagLimit:** Limiting magnitude of objects to be matched with the standard stars from the input catalog.

**MinStars:** Minimum required number of stars for the creation of a star match table.

**ReduceAnyFrame:** Normally the *vmimstandard* recipe would attempt to reduce any dataset classified as a standard stars field exposure. However, during the time critical on-line processing, it may be appropriate not to reduce systematically all the incoming frames. This is because the same standard stars field is exposed once for each VIMOS quadrant, and to reduce images from the temporarily unused quadrants is not a requirement. Setting this parameter to *false* would prevent the processing of such images. For an off-line processing this parameter would be typically set to *true*.

**SearchRadius:** Max distance (in arcseconds) from the expected position of a catalog star.

**StarIndex:** This index can have a value between 0 (minimal stellarity) and 1 (maximal stellarity). Only the identified objects having a stellarity index greater than the specified value will be taken as stars, to be matched with the standard stars from the input catalog.

**TemperatureCheck:** For associating the detected stars with the reference catalog, their coordinates must be corrected applying the CCD to Sky distortion corrected for changes in the beam temperature (see Sections 8.2.2 and 9.17). If this parameter is set, the beam temperature is compared with the temperatures of the other beams and with the ambient temperature. If the difference between the beam temperature and the ambient temperature is greater than the threshold specified by *TemperatureTolerance*, then the

temperature used will be the mean of the beams temperatures that differ from the ambient temperature less than the specified threshold. If not a single beam temperature is within tolerance, then the ambient temperature is used in place of the beam temperature. This option was just introduced to prevent possible problems with the beam temperature sensors.

**TemperatureTolerance:** Max tolerated difference between ambient and beam temperatures. This parameter is effective only if *TemperatureCheck* is set.

A description of the algorithms used in this recipe is given in Section 9.18, page 155.

## 7.9 vmimcalphot

The VIMOS pipeline recipe *vmimcalphot* is used to determine night zeropoints, atmospheric extinction coefficients, and colour terms, from a set of star match tables produced by the recipe *vmimstandard* (see Section 7.8, page 81). The star match tables may refer to different standard star fields, but they must all be derived from exposures made with the same filter and the same quadrant.

The files to be included in the input SOF are all listed in Table 7.9.1.

DO category	Type	Explanation	Required
IMG_STAR_MATCH_TABLE	Pipeline product	List of identified standard stars	✓
PHOTOMETRIC_TABLE	Calibration	Photometric table	✓

Table 7.9.1: *Input files for the vmimcalphot recipe.*

The standard photometric tables in the calibration directories are named *ipc\_f.q.tfits* (where *f* is the filter name and *q* the quadrant number).

The only product of this recipe is an upgraded PHOTOMETRIC\_TABLE (Table 7.8.2, page 82), carrying the newly computed zeropoint, and, if requested, new extinction and colour coefficients.

File name	DO category	Type	Explanation
photometric_table.fits	PHOTOMETRIC_TABLE	FITS	Upgraded photometric table

Table 7.9.2: *Product of the vmimcalphot recipe.*

The *vmimcalphot* parameters are listed in Table 7.9.3.

A more complete description of the parameters meaning is also given:

**ColorTerm:** If both this and the *Extinction* parameters are set, the difference between the catalog magnitude and the instrumental magnitude of all stars is seen as a function of the airmass and of the star colour index; a first order bivariate linear fit is then made to derive simultaneously the extinction coefficient and the colour term (beside the magnitude zeropoint). Alternatively, if *Extinction* is false, the difference between the catalog magnitude and the instrumental magnitude is seen just as a function of the star

Parameter	Possible values	Explanation
Extinction	true	Compute the extinction coefficient
	false	Do not compute the extinction coefficient
ColorTerm	true	Compute the colour term
	false	Do not compute the colour term
UseColorTerm	true	Use colour term in zeropoint computation
	false	Do not use colour term in zeropoint computation

Table 7.9.3: *vmimcalphot* parameters.

colour index, and in this case a linear fit between colour index and magnitude difference is made. If the computation of the extinction coefficient is requested, at least four star match tables obtained from observations at different airmasses should be specified in input. Otherwise, it is advisable to specify just one input star match table (*i.e.*, with all stars at the same airmass), containing at least four stars with different colour indexes.

**Extinction:** The case in which both this and the *ColorTerm* parameters are set is described above. Alternatively, if *ColorTerm* is false, the difference between the catalog magnitude and the instrumental magnitude is seen just as a function of the star airmass, and in this case a linear fit between airmass and magnitude difference is made. At least four star match tables obtained from observations made at different airmasses should be specified in input.

**UseColorTerm:** This parameter is only effective if both the *ColorTerm* and the *Extinction* parameters are off. In this case, before being averaged, the difference between the catalog magnitude and the instrumental magnitude is corrected for the atmospheric extinction. If the *UseColorTerm* parameter is set, the magnitude difference is also corrected for the colour index of each star. The estimates of the colour and the atmospheric extinction coefficients used for these corrections are read from the input photometric table.

A description of the algorithms used in this recipe is given in Section 9.19, page 155.

## 7.10 vmimpreimaging

The VIMOS pipeline recipe *vmimpreimaging* is used to apply basic reduction steps to the imaging observation that is preliminary to a MOS observation of the same field. No source detection is attempted on the image. The image WCS, together with the component describing the instrument optical distortions (see Section 8.2.2, page 134), is converted into the convention followed by VMMPs (the VIMOS mask preparation software). This set of coefficients, the so-called CO-matrix used by the SAO WCSTools package [10], is written to the header of the reduced image.

The files to be included in the input SOF are listed in Table 7.10.1.

The bad pixel table needs to be specified only if the cleaning of bad pixels is requested. If a photometric table is specified, the magnitude zeropoint, the atmospheric extinction coefficient, and the colour term (see Table 7.8.2, page 82) are copied from the photometric table to the header of the reduced image.

The products of the *vmimpreimaging* recipe are shown in Table 7.10.2.

DO category	Type	Explanation	Required
IMG_PREIMAGING	Raw frame	Preimaging exposure	✓
MASTER_BIAS	Calibration	Master bias	✓
IMG_MASTER_SKY_FLAT	Calibration	Master sky flat field	✓
CCD_TABLE	Calibration	Bad pixel table	
PHOTOMETRIC_TABLE	Calibration	Photometric table	

Table 7.10.1: *Input files for the vmimpreimaging recipe.*

File name	DO category	Type	Explanation
img_science_reduced.fits	IMG_SCIENCE_REDUCED	FITS	Reduced preimaging exposure

Table 7.10.2: *Product of the vmimpreimaging recipe.*

The *vmimpreimaging* parameters are listed in Table 7.10.3.

Parameter	Possible values	Explanation
BiasMethod	Master Zmaster	Bias removal with no overscan correction Bias removal with overscan correction
CleanBadPixel	true false	Clean bad pixels Do not clean bad pixels
CleanCosmic	true false	Clean cosmic rays Do not clean cosmic rays
CosmicThreshold	<i>float</i>	Sigmas above level discriminator
CosmicRatio	<i>float</i>	Peak/neighbours discriminator
TemperatureCheck	true false	Check beam and ambient temperatures consistency Do not check consistency of temperatures
TemperatureTolerance	<i>float</i> ( $^{\circ}C$ )	Max difference beam - ambient temperatures

Table 7.10.3: *vmimpreimaging parameters.*

A more complete description of the parameters is also given here:

**BiasMethod:** Method for bias removal from the input exposure. The bias removal procedure is described in some detail in Section 9.3. Possible settings are:

**Master:** After master bias subtraction, prescan and overscan regions are trimmed away from the input frame.

**Zmaster:** After master bias subtraction the overscan correction is applied before trimming away the overscan regions.

**CleanBadPixel:** Bad pixel correction on the reduced exposure. If this option is turned on, a bad pixel table should be specified in the input SOF (see Table 7.8.1). The bad pixel correction algorithm is described in Section 9.1, page 141.



**CleanCosmic:** Cosmic ray events removal from input raw frame. The cosmic ray rejection algorithm is described in Section 9.2, page 142.

**CosmicRatio:** Critical ratio for discriminating between objects and cosmic rays. This parameter is effective when *CleanCosmic* is set.

**CosmicThreshold:** Threshold for the selection of cosmic rays candidates. This parameter is effective when *CleanCosmic* is set.

**TemperatureCheck:** The Sky to CCD distortion models (see 8.2.2, page 134) may require to be corrected for thermal expansion effects on the camera and the CCD, before converting them into the CO-matrix convention. If this parameter is set, the beam temperature is compared with the temperatures of the other beams and with the ambient temperature. If the difference between the beam temperature and the ambient temperature is greater than the threshold specified by *TemperatureTolerance*, then the temperature used will be the mean of the beams temperatures that differ from the ambient temperature less than the specified threshold. If not a single beam temperature is within tolerance, then the ambient temperature is used in place of the beam temperature. This option was just introduced to prevent possible problems with the beam temperature sensors.

**TemperatureTolerance:** Max tolerated difference between ambient and beam temperatures. This parameter is effective only if *TemperatureCheck* is set.

A description of the algorithms used in this recipe is given in Section 9.20, page 155.

## 7.11 vmimobsstare

The VIMOS pipeline recipe *vmimobsstare* is used to apply basic reduction steps to one exposure made in direct imaging mode. SExtractor v2.1.6 [8] is run on the reduced image, producing a table of detected objects with their instrumental magnitudes, their celestial and image coordinates, and their stellarity index. The image WCS, together with the component describing the instrument optical distortions (see Section 8.2.2, page 134), is converted into the convention followed by VMPS (the VIMOS mask preparation software). This set of coefficients, the CO-matrix used in the SAO WCSTools package [10], is written to the header of the reduced image.

The files to be included in the input SOF are listed in Table 7.11.1.

DO category	Type	Explanation	Required
IMG_SCIENCE	Raw frame	Science exposure	✓
MASTER_BIAS	Calibration	Master bias	✓
MASTER_DARK	Calibration	Master dark	
IMG_MASTER_SKY_FLAT	Calibration	Master sky flat field	✓
CCD_TABLE	Calibration	Bad pixel table	
PHOTOMETRIC_TABLE	Calibration	Photometric table	

Table 7.11.1: *Input files for the vmimobsstare recipe.*

The bad pixel table needs to be specified only if the cleaning of bad pixels is requested. In the calibration directories there is one CCD\_TABLE file for each quadrant, named `badpixel.q.tfits` (where  $q$  is the quadrant number). Care should be taken in selecting the appropriate bad pixel tables for the imaging instrument mode (in the case of spectral data  $q$  is the quadrant number increased by 4).

If a photometric table is specified, the magnitude zeropoint, the atmospheric extinction coefficient, and the colour term (see Table 7.8.2, page 82) are copied from the photometric table to the header of the reduced image. The standard photometric tables in the calibration directories are named `ipc_f.q.tfits` (where  $f$  is the filter name and  $q$  the quadrant number).

The products of the `vmimobsstare` recipe are shown in Table 7.11.2.

File name	DO category	Type	Explanation
<code>img_science_reduced.fits</code>	IMG_SCIENCE_REDUCED	FITS	Reduced imaging exposure
<code>img_galaxy_table.fits</code>	IMG_GALAXY_TABLE	FITS	List of detected objects

Table 7.11.2: *Product of the vmimobsstare recipe.*

The galaxy table is the output of SExtractor [8] converted into FITS format, and it is shown in Table 7.11.3. The content of this table is defined within the VIMOS pipeline DRS, with the only intent of serving the purpose of the involved pipeline recipes. Some of the table columns listed contain data necessary for the computation of QC parameters (see ahead), while objects positions and magnitudes are necessary for the identification of standard photometric and astrometric stars in the `vmimstandard` and the `vmiskyccd` recipes. For a customised output it is always possible to run SExtractor separately, after configuring the native SExtractor parameter files. For a complete explanation of the output parameters please refer to the SExtractor documentation (that can be found in [http://terapix.iap.fr/rubrique.php?id\\_rubrique=91/index.html](http://terapix.iap.fr/rubrique.php?id_rubrique=91/index.html)).

The `vmimobsstare` parameters are listed in Table 7.11.4. Only few parameters of the SExtractor group are listed here: almost all entries of the SExtractor configuration file, `$PIPE_HOME/vimos/config/vimos.sex`, can be overruled by the SExtractor group parameter values specified in the `vmimobsstare.rc` configuration file. Conventionally, a SExtractor configuration parameter name matches the `vmimobsstare` configuration parameter obtained by lowercasing all of its characters with the exception of the first character of each word, and removing the underscore. For instance, the SExtractor parameter `CATALOG_TYPE` matches the `vmimobsstare` parameter `CatalogType`. When using the corresponding command line option, the SExtractor group must be explicitly specified. For instance, the command option corresponding to the parameter `CatalogType` is `--SExtractor.CatalogType`.

The `Window` parameter has no counterpart in the SExtractor configuration file, and is used to restrict the SExtractor operations to just a part of the input image. This is useful to avoid false detections along the vignetted image region.

Column name	Explanation
NUMBER	Object number
MAG_ISOCOR	Corrected isophotal magnitude
MAGERR_ISOCOR	RMS error on corrected isophotal magnitude
MAG_APER	Fixed-aperture magnitude
MAGERR_APER	RMS error on fixed-aperture magnitude
MAG_AUTO	Automatic-aperture magnitude
MAGERR_AUTO	RMS error on automatic-aperture magnitude
MAG_BEST	MAG_AUTO if no neighbours, otherwise MAG_ISOCOR
MAGERR_BEST	Error on instrumental magnitude
X_IMAGE	Object X pixel position
Y_IMAGE	Object Y pixel position
X_WORLD	Object RA
Y_WORLD	Object Dec
ISOAREA_WORLD	Area of lowest isophote (arcsec <sup>2</sup> )
A_IMAGE	2 <sup>nd</sup> order moment along the major axis (pixel)
B_IMAGE	2 <sup>nd</sup> order moment along the minor axis (pixel)
A_WORLD	2 <sup>nd</sup> order moment along the major axis (arcsec)
B_WORLD	2 <sup>nd</sup> order moment along the minor axis (arcsec)
FWHM_IMAGE	FWHM (pixel) of mean radial profile (gaussian fit)
FWHM_WORLD	FWHM (arcsec) of mean radial profile
THETA_IMAGE	PA of major axis (counter-clockwise from X axis)
ERRTHETA_IMAGE	Error on Position Angle
ELLIPTICITY	$1 - B\_IMAGE / A\_IMAGE$
CLASS_STAR	Stellarity index, 0.0 = galaxy, 1.0 = star
FLAGS	Extraction flag, different from 0 in case of error

Table 7.11.3: *Galaxy table entries.*

Parameter	Possible values	Explanation
BiasMethod	Master Zmaster	Bias removal with no overscan correction Bias removal with overscan correction
CleanBadPixel	true false	Clean bad pixels Do not clean bad pixels
CleanCosmic	true false	Clean cosmic rays Do not clean cosmic rays
CosmicThreshold	<i>float</i>	Sigmas above level discriminator
CosmicRatio	<i>float</i>	Peak/neighbours discriminator
TemperatureCheck	true false	Check beam and ambient temperatures consistency Do not check consistency of temperatures
TemperatureTolerance	<i>float</i> ( $^{\circ}C$ )	Max difference beam - ambient temperatures
StarIndex	<i>float</i>	Min stellarity index for stars selection
ComputeQC	true false	Compute QC parameters Do not compute QC parameters
SExtractor.FilterName	<i>file</i>	SExtractor convolution mask
SExtractor.SExtractor	<i>file</i>	SExtractor executable
SExtractor.StarNnwName	<i>file</i>	SExtractor neural network weights
SExtractor.Window	<i>file</i>	Image region where SExtractor is applied

Table 7.11.4: *vmimobsstare* parameters.

A more complete description of the parameters not belonging to the SExtractor group is given here:

**BiasMethod:** Method for bias removal from the input exposure. The bias removal procedure is described in some detail in Section 9.3. Possible settings are:

**Master:** After master bias subtraction, prescan and overscan regions are trimmed away from the input frame.

**Zmaster:** After master bias subtraction the overscan correction is applied before trimming away the overscan regions.

**CleanBadPixel:** Bad pixel correction on the reduced exposure. If this option is turned on, a bad pixel table should be specified in the input SOF (see Table 7.8.1). The bad pixel correction algorithm is described in Section 9.1, page 141.

**CleanCosmic:** Cosmic ray events removal from input raw frame. The cosmic ray rejection algorithm is described in Section 9.2, page 142.

**ComputeQC:** If this parameter is set, *Quality Control* (QC) parameters will be computed and written partly to the header of the output galaxy table and partly to the header of the reduced standard field frame (depending on the dataset used for their computation). They will also be written to two output QC PAF files named `qc0000.paf` and `qc0001.paf`. These files are not classified as pipeline recipe products, as they are intermediate datasets that in the standard pipeline operations would be translated into new entries in the QC log file.

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The QC parameters computed from the contents of the galaxy table are based only on the objects with `FLAGS = 0`. In particular, all the objects in the galaxy table having a stellarity index greater than the value specified at the parameter *StarIndex* are here called “stars” for simplicity:

- QC IMAGE QUALITY: The image quality is computed as a robust estimate of the parameter `FWHM_WORLD` of all the stars in the galaxy table. Starting from the median value of `FWHM_WORLD`, the standard deviation from this value is used to exclude outliers, and to compute an improved estimate of the seeing. This operation is then iterated, up to four times.
- QC IMAGE QUALITY ERROR: The error on QC IMAGE QUALITY is given as the population standard deviation of the `FWHM_WORLD` values contributing to the final mean.
- QC STAR COUNT: Number of stars in galaxy table.
- QC STELLARITY MEAN: Mean stellarity index of all objects in the galaxy table.
- QC STELLARITY RMS: Population standard deviation of the stellarity indexes of all objects in the galaxy table.
- QC STAR STELLARITY MEAN: Mean stellarity index of all stars in the galaxy table.
- QC STAR STELLARITY RMS: Population standard deviation of the stellarity indexes of all stars in the galaxy table.
- QC STAR ELLIPTICITY MEAN: Mean value of the parameter `ELLIPTICITY` of all the stars in the galaxy table.
- QC STAR ELLIPTICITY RMS: Population standard deviation of the `ELLIPTICITY` of all the stars in the galaxy table.
- QC STAR ORIENTATION MEAN: Mean orientation of star ellipses, from  $-90$  to  $+90$  degrees, counted counterclockwise, with 0 corresponding to the image X axis. This parameter is determined by a peak detection algorithm run on an histogram of all objects orientations. Initially, an approximate position of the most probable orientation is determined. Then a new histogram is built, centred on this position and with a number of bins dependent on the number of objects available, and a more accurate peak detection algorithm is run again. If no peak is detected, this parameter is assigned the value zero, associated to an error of  $\pm 90$  degrees (this is good for plots).
- QC STAR ORIENTATION RMS: Sigma of mean orientation of star ellipses. This is the uncertainty on the position of the maximum of a gaussian fit to the detected peak. If no peak were detected, this parameter would be assigned the value of 90 degrees.
- QC MAGLIM: Limiting magnitude. All the stars in the galaxy table are selected, and a histogram of their magnitudes is built. Bin sizes from 0.1 up to 1.0 magnitudes are tried, until the most populated bin contains at least 20 stars. The position of the most populated bin is taken as the limiting magnitude. If the 20 stars level for the highest bin is never reached, the limiting magnitude value is set to 0.0.
- QC MAGLIM ERROR: The error is taken as the value of the bin size of the histogram used in the determination of the limiting magnitude. If no limiting magnitude were found, the error would be set to 0.0.

The only QC parameters computed from the reduced image are the following, and are written to the header of the reduced image itself:

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**QC SKYBACK :** The sky background (in ADU/s) is evaluated dividing the central 1600x1800 region of the chip into 10x10 regions 160x180 pixels each. For each region the median level is computed. The mean of the 10 lowest values obtained is the estimation of the sky background level. This value is scaled to the unit of time.

**QC SKYBACK ERROR :** The error on **QC SKYBACK** is taken as the population RMS of the 10 values used in the estimation of the sky background level.

**CosmicRatio:** Critical ratio for discriminating between objects and cosmic rays. This parameter is effective when *CleanCosmic* is set.

**CosmicThreshold:** Threshold for the selection of cosmic rays candidates. This parameter is effective when *CleanCosmic* is set.

**StarIndex:** This parameter is only effective when *ComputeQC* is set. All the galaxy table objects with a stellarity index greater than the specified value are taken as stars.

**TemperatureCheck:** The Sky to CCD distortion models (see 8.2.2, page 134) may require to be corrected for thermal expansion effects on the camera and the CCD, before converting them into the CO-matrix convention. If this parameter is set, the beam temperature is compared with the temperatures of the other beams and with the ambient temperature. If the difference between the beam temperature and the ambient temperature is greater than the threshold specified by *TemperatureTolerance*, then the temperature used will be the mean of the beams temperatures that differ from the ambient temperature less than the specified threshold. If not a single beam temperature is within tolerance, then the ambient temperature is used in place of the beam temperature. This option was just introduced to prevent possible problems with the beam temperature sensors.

**TemperatureTolerance:** Max tolerated difference between ambient and beam temperatures. This parameter is effective only if *TemperatureCheck* is set.

A description of the algorithms used in this recipe is given in Section 9.21, page 156.

## 7.12 vmimobsjitter

The VIMOS pipeline recipe *vmimobsjitter* is used to apply basic reduction steps to a sequence of exposures made in direct imaging mode, and to combine them in a single image. Each input image is processed in the same way as by recipe *vmimobsstare*, therefore what characterises the *vmimobsjitter* is just the final combination of the input frames, and the optional sky fringing removal.

The input and the output files are the same listed for the recipe *vmimobsstare* in the Tables 7.11.1 and 7.11.2, page 89. The only exception is the sky fringes map, `IMG_FRINGES`, that is additionally created by *vmimobsjitter* when the fringing correction is requested.

The *vmimobsjitter* parameters are listed in Table 7.12.1.

Parameter	Possible values	Explanation
BiasMethod	Master Zmaster	Bias removal with no overscan correction Bias removal with overscan correction
CleanBadPixel	true false	Clean bad pixels Do not clean bad pixels
FringingCorr	true false	Apply sky fringing correction Do not apply sky fringing correction
Resampling	BiLinear BiCubic	Pixel value bilinear interpolation Pixel value bicubic interpolation
StackMethod	Average Median MinMax Ksigma Auto	Average combination of reduced images Median combination of reduced images Min-max combination of reduced images K-sigma clipping combination of reduced images Optimal combination of reduced images
KSigmaLow	<i>float</i> (sigma)	Low threshold for K-sigma clipping method
KSigmaHigh	<i>float</i> (sigma)	High threshold for K-sigma clipping method
MaxRejection	<i>int</i>	Number of highest values excluded in rejection stack method
MinRejection	<i>int</i>	Number of lowest values excluded in rejection stack method
TemperatureCheck	true false	Check beam and ambient temperatures consistency Do not check consistency of temperatures
TemperatureTolerance	<i>float</i> (°C)	Max difference beam - ambient temperatures
StarIndex	<i>float</i>	Min stellarity index for stars selection
ComputeQC	true false	Compute QC parameters Do not compute QC parameters
SExtractor.FilterName	<i>file</i>	SExtractor convolution mask
SExtractor.SExtractor	<i>file</i>	SExtractor executable
SExtractor.StarNnwName	<i>file</i>	SExtractor neural network weights
SExtractor.Window	<i>file</i>	Image region where SExtractor is applied

Table 7.12.1: *vmimobsjitter* parameters.

Only few parameters of the SExtractor group are listed here: almost all the entries of the SExtractor configuration file, `$PIPE_HOME/vimos/config/vimos.sex`, can be overruled by the SExtractor group parameter

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values specified in the `vmimobsjitter.rc` configuration file. Conventionally, a SExtractor configuration parameter name matches the `vmimobsjitter` configuration parameter obtained by lowercasing all of its characters with the exception of the first character of each word, and removing the underscore. For instance, the SExtractor parameter `CATALOG_TYPE` matches the `vmimobsstare` parameter *CatalogType*. When using the corresponding command line option, the SExtractor group must be explicitly specified. For instance, the command option corresponding to the parameter *CatalogType* is `--SExtractor.CatalogType`.

The *Window* parameter has no counterpart in the SExtractor configuration file, and is used to restrict the SExtractor operations to just a part of the input image. This is useful to avoid false detections along the vignetted image region.

A more complete description of the parameters not belonging to the SExtractor group is given here:

**BiasMethod:** Method for bias removal from the input exposures. The bias removal procedure is described in some detail in Section 9.3. Possible settings are:

**Master:** After master bias subtraction, prescan and overscan regions are trimmed away from the input frames.

**Zmaster:** After master bias subtraction the overscan correction is applied before trimming away the overscan regions.

**CleanBadPixel:** Bad pixel correction on each reduced exposure, before combination. If this option is turned on, a bad pixel table should be specified in the input SOF (see Table 7.8.1). The bad pixel correction algorithm is described in Section 9.1, page 141.

**ComputeQC:** If this parameter is set, *Quality Control* (QC) parameters will be computed. The QC parameters are computed on the combined image, and are the same parameters that are computed in recipe *vmimobsstare* (see Section 7.11, page 89).

**FringingCorr:** Sky fringing removal from product frame. If this parameter is set, a sky+fringe map is generated by median-stacking all the bias subtracted input raw frames. This image, containing both fringes and mean sky level, is finally subtracted from each input frame. After this, the data reduction proceeds in the usual way.

**KSigmaHigh:** Number of standard deviations above the median pixel value for rejecting a pixel value when *StackMethod* is set to “*Ksigma*”.

**KSigmaLow:** Number of standard deviations below the median pixel value for rejecting a pixel value when *StackMethod* is set to “*Ksigma*”.

**MaxRejection:** Number of highest pixel values to be rejected when *StackMethod* is set to “*MinMax*”.

**MinRejection:** Number of lowest pixel values to be rejected when *StackMethod* is set to “*MinMax*”.

**Resampling:** Method used for interpolating pixel values from a single reduced frame to the common pixelisation defined for the combined image. Possible settings are:

**BiLinear:** Bilinear interpolation.



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**BiCubic:** Bicubic interpolation.

**StackMethod:** Method used for combination of reduced images. See Section 9.6 for a complete description of all the combination methods. Possible settings are:

**Auto:** Given the number of input frames, an optimal frame combination method is selected. Currently this is always going to the method “*Average*”.

**Average:** The combined frame is the mean of the input frames.

**Ksigma:** The combined frame is the mean of the input frames, after K-sigma screening of pixel values. The number of sigma to be applied in the rejection is specified by the parameters *KSigmaLow* and *KSigmaHigh*.

**Median:** The combined frame is the median of the input frames.

**MinMax:** The combined frame is the mean of the input frames, after rejection of minimum and maximum values. The number of values to reject is specified by the parameters *MinRejection* and *MaxRejection*.

**StarIndex:** This parameter is only effective when *ComputeQC* is set. All the galaxy table objects with a stellarity index greater than the specified value are taken as stars.

**TemperatureCheck:** The Sky to CCD distortion models (see 8.2.2, page 134) may require to be corrected for thermal expansion effects on the camera and the CCD, before converting them into the CO-matrix convention. If this parameter is set, the beam temperature is compared with the temperatures of the other beams and with the ambient temperature. If the difference between the beam temperature and the ambient temperature is greater than the threshold specified by *TemperatureTolerance*, then the temperature used will be the mean of the beams temperatures that differ from the ambient temperature less than the specified threshold. If not a single beam temperature is within tolerance, then the ambient temperature is used in place of the beam temperature. This option was just introduced to prevent possible problems with the beam temperature sensors.

**TemperatureTolerance:** Max tolerated difference between ambient and beam temperatures. This parameter is effective only if *TemperatureCheck* is set.

A description of the algorithms used in this recipe is given in Section 9.22, page 156.

### 7.13 vmspflat

The VIMOS pipeline recipe *vmspflat* is used to create the MOS normalised master flat field from a set of MOS flat field exposures. A not normalised master flat field is also required by the recipe *vmspcaldisp* to determine the spatial curvature model (see Section 8.3.3, page 137). The recipe *vmspflat* does compute its own curvature model, but this is generally incompatible with the wavelength calibration and the optical distortion models computed by *vmspcaldisp*. For this reason this curvature model is just used internally in the process of flat field normalisation, where the compatibility with the *Y* component of the optical distortion model is irrelevant (see Sections 8.3.2 through 8.3.4).

The files to be included in the input SOF are listed in Table 7.13.1.

DO category	Type	Explanation	Required
MOS_SCREEN_FLAT	Raw frame	Flat field exposures	✓
MASTER_BIAS	Calibration	Master bias	✓
MASTER_DARK	Calibration	Master dark	
GRISM_TABLE	Calibration	Grism table	✓
CCD_TABLE	Calibration	Bad pixel table	

Table 7.13.1: *Input files for the vmspflat recipe.*

At least one raw flat field exposure should be present in the input SOF. The acquisition of input flat fields may be done using different mask shutter settings (to avoid contamination between different spectral orders in LR grisms used with multiplexed masks, see Figure 7.14.1, page 107). The *vmspflat* recipe will properly combine all the input frames according to a specified method.<sup>11</sup>

The bad pixel table needs to be specified only if the cleaning of bad pixels is requested. In the calibration directories there is one CCD\_TABLE file for each quadrant, named `badpixel.q.tfits` (where *q* is the quadrant number increased by 4). Care should be taken in selecting the appropriate bad pixel tables for the spectral instrument mode (in the case of imaging data *q* is the quadrant number).

The grism table is required by all VIMOS pipeline MOS recipes. It contains necessary information to control the way spectra are extracted, and the determination of the spectral distortion models. The *vmspflat* recipe gets from the grism table the wavelength that should be used as reference (header entry PRO WLEN CEN), and the spectrum extension in CCD pixels above and below the position of the reference wavelength (header entries PRO SPECT LLEN LO and PRO SPECT LLEN HI) (see Figure 8.3.1, page 138). In the calibration directories there is one GRISM\_TABLE file for each quadrant/grism combination, named `grs_grism.q.tfits` (where *grism* is the grism name, and *q* is the quadrant number).

The products of the *vmspflat* recipe are shown in Table 7.13.2.

File name	DO category	Type	Explanation
<code>mos_master_screen_flat.fits</code>	MOS_MASTER_SCREEN_FLAT	FITS	Normalised flat field
<code>mos_combined_screen_flat.fits</code>	MOS_COMBINED_SCREEN_FLAT	FITS	Total flat field
<code>vmCrvOpt-q.paf</code>		PAF	CRV and OPT models

Table 7.13.2: *Products of the vmspflat recipe.*

The PAF file just contains the curvature and the optical distortion models computed in the process of spectra normalisation. Such models are available just for debug purposes, and are not to be used in further data reduction steps.

<sup>11</sup>This has not yet been tested with real data.

The *vmisflat* parameters are listed in Table 7.13.3.

Parameter	Possible values	Explanation
BiasMethod	Master Zmaster	Bias removal with no overscan correction Bias removal with overscan correction
CleanBadPixel	true false	Clean bad pixels Do not clean bad pixels
CleanCosmic	true false	Clean cosmic rays Do not clean cosmic rays
ComputeQC	true false	Compute QC parameters Do not compute QC parameters
FlatMethod	Average Median Polynomial	Model flat field trends by average filtering Model flat field trends by median filtering Model flat field trends by polynomial fitting
Fuzz	<i>int</i> (pixel)	Extra $X$ pixels in spectral extraction
KSigmaLow	<i>float</i>	Low threshold for K-sigma clipping stack method
KSigmaHigh	<i>float</i>	High threshold for K-sigma clipping stack method
MaxRejection	<i>int</i>	Number of highest values excluded in rejection stack method
MinRejection	<i>int</i>	Number of lowest values excluded in rejection stack method
PolyOrderX	<i>float</i>	Degree of polynomial for $X$ trend removal
PolyOrderY	<i>float</i>	Degree of polynomial for $Y$ trend removal
SmoothBoxSize	<i>int</i>	Filter box size used in trend removal
StackMethod	Average Ksigma MinMax Median	Combined flat field is the average of the input frames Flat fields are combined with a K-sigma clipping method Flat fields are combined with a min-max rejection method Flat fields are combined with a median method

Table 7.13.3: *vmisflat* parameters.

A more complete description of the used parameters meaning is given here:

**BiasMethod:** Method for bias removal from the input spectral flat field frames. The bias removal procedure is described in some detail in Section 9.3. Possible settings are:

**Master:** After master bias subtraction, prescan and overscan regions are trimmed away from the flat field frame.

**Zmaster:** After master bias subtraction the overscan correction is applied before trimming away the overscan regions.

**CleanBadPixel:** Bad pixel correction on the output master spectral flat field. If this option is turned on, a bad pixel table should be specified in the input SOF (see Table 7.13.1). The bad pixel correction algorithm is described in Section 9.1, page 141.

**CleanCosmic:** Cosmic ray events removal from input raw spectral flat field frames. The cosmic ray rejection algorithm is described in Section 9.2, page 142.

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**ComputeQC:** If this parameter is set, *Quality Control* (QC) parameters will be computed and written to the header of the output normalised master flat field and to an output QC PAF file named `qc0000.paf`. This file is not classified as a pipeline recipe product, as it is an intermediate dataset that in the standard pipeline operations would be translated into new entries in the QC log file. Currently the QC parameters computed by *vmsflat* are:

QC MOS SLIT WIDTH: Width (in mm) of slit closest to mask centre.

QC MOS FLAT FLUX: The position of the slit closest to the mask centre is determined. For this slit the position of the reference wavelength is determined applying the available spectral distortion models. The total counts in the rectangular region long as the slit length in pixels, 5 CCD pixels wide, and centred at the reference wavelength position, are then bias subtracted and divided by the area of the slit and by the exposure time. The flux is given in  $\text{ADU s}^{-1}\text{mm}^{-2}$ .

QC MOS FLAT FLUXERR: The total counts in the rectangular region where the flux was determined are square-rooted, and then normalised to the unit of area and time.

**FlatMethod:** Method used in modeling each slit spectrum, for removing the large scale trends related to the CCD intrinsic response with changing wavelength. Possible settings are:

**Average:** Average filter. The smooth box is defined by the parameter *SmoothBoxSize*.

**Median:** Median filter. The smooth box is defined by the parameter *SmoothBoxSize*.

**Polynomial:** Polynomial fitting of spectrum. This method gives generally bad results, and its use is not advisable. The order of the fitting polynomial is specified by the parameters *PolyOrderX* and *PolyOrderY*.

**Fuzz:** Extra number of *X* CCD pixels, to be added at the spectra sides during the extraction. This parameter is just used when flat fields acquired with different mask shutter positions are input to the recipe (see Section 9.23, page 157).

**KSigmaHigh:** Number of standard deviations above the median pixel value for rejecting a pixel value when *StackMethod* is set to “*Ksigma*”.

**KSigmaLow:** Number of standard deviations below the median pixel value for rejecting a pixel value when *StackMethod* is set to “*Ksigma*”.

**MaxRejection:** Number of highest pixel values to be rejected when *StackMethod* is set to “*MinMax*”.

**MinRejection:** Number of lowest pixel values to be rejected when *StackMethod* is set to “*MinMax*”.

**PolyOrderX:** Degree of polynomial used for fitting the flat spectrum in the cross-dispersion direction. Used if *FlatMethod* is set to “Polynomial”.

**PolyOrderY:** Degree of polynomial used for fitting the flat spectrum in the dispersion direction. Used if *FlatMethod* is set to “Polynomial”.

**SmoothBoxSize:** Size of the running box used for smoothing, expressed as number of pixels along the dispersion direction. This parameter is ignored if *FlatMethod* is set to “Polynomial”.

**StackMethod:** Combination method of input flat fields taken with the same mask shutters position. See Section 9.6 for a complete description of all the combination methods. Possible settings are:

**Average:** The combined flat field is the mean of the input frames.

**Ksigma:** The combined flat field is the mean of the input frames, after K-sigma screening of pixel values. The number of sigma to be applied in the rejection is specified by the parameters *KSigmaLow* and *KSigmaHigh*.

**Median:** The combined flat field is the median of the input frames.

**MinMax:** The combined flat field is the mean of the input frames, after rejection of minimum and maximum values. The number of values to reject is specified by the parameters *MinRejection* and *MaxRejection*.

A description of the algorithms used in this recipe is given in Section 9.23, page 157.

## 7.14 vmspcaldisp

The VIMOS pipeline recipe *vmspcaldisp* is used to determine all the spectral distortions and transformations (see Section 8.3, pages 135-140) from an arc lamp exposure and a combined flat field produced by the recipe *vmspflat*.

The files to be included in the input SOF are listed in Table 7.14.1.

DO category	Type	Explanation	Required
MOS_ARC_SPECTRUM	Raw frame	Arc lamp exposure	✓
MASTER_BIAS	Calibration	Master bias	✓
MASTER_DARK	Calibration	Master dark	
MOS_MASTER_SCREEN_FLAT	Calibration	Normalised flat field	
MOS_COMBINED_SCREEN_FLAT	Calibration	Combined flat field	
GRISM_TABLE	Calibration	Grism table	✓
LINE_CATALOG	Calibration	Line catalog	✓
EXTRACT_TABLE	Calibration	Extraction table	
CCD_TABLE	Calibration	Bad pixel table	

Table 7.14.1: *Input files for the vmspcaldisp recipe.*

At least one raw arc lamp exposure should be present in the input SOF. In general the acquisition of input arc lamp exposures may be done using different mask shutter settings (to avoid contamination between different spectral orders in LR grisms used with multiplexed masks, see Figure 7.14.1, page 107). The *vmspcaldisp* recipe will properly combine all the input frames according to a specified method.<sup>12</sup>

The normalised and the combined flat fields are the products of the recipe *vmspflat* run on flat field data obtained with the same mask. Neither of them is required for running *vmspcaldisp*, but if a combined flat field is not

<sup>12</sup>This has not yet been tested with real data.

given then no spatial curvature model can be computed, and a “first guess” is used in its place. A normalised master flat field needs to be specified only if a flat field correction is requested.

The bad pixel table needs to be specified only if the cleaning of bad pixels is requested. In the calibration directories there is one CCD\_TABLE file for each quadrant, named `badpixel.q.tfits` (where  $q$  is the quadrant number increased by 4). Care should be taken in selecting the appropriate bad pixel tables for the spectral instrument modes (in the case of imaging data  $q$  is the quadrant number).

An extraction table produced by previous runs of *vmspcaldisp* (see below) may be specified in input. In this way, the global spectral distortion models it carries would be used as first-guesses, instead of those carried in the arc lamp exposure header. This would allow to easily iterate the distortion models computed by this recipe, till the desired accuracy is reached.

The grism table is required by all VIMOS pipeline MOS recipes. It contains necessary information to control the way spectra are extracted and the determination of the distortion models. The *vmspcaldisp* recipe gets from the grism table the wavelength that should be used as reference (header entry `PRO WLEN CEN`), and the spectrum extension in CCD pixels above and below the position of the reference wavelength (header entries `PRO SPECT LLEN LO` and `PRO SPECT LLEN HI`) (see Figure 8.3.1, page 138). Other parameters, used in the construction of the extracted arc lamp slit spectra (see Table 7.14.2), are the start and the end wavelength of the image containing the extracted spectra (header entries `PRO WLEN START` and `PRO WLEN END`), and the step of the sampling along the dispersion direction (header entry `PRO WLEN INC`). In the calibration directories there is one GRISM\_TABLE file for each quadrant/grism combination, named `grs_grism.q.tfits` (where *grism* is the grism name, and  $q$  is the quadrant number).

The line catalogues in the calibration directories are also named `lcat_grism.q.tfits` although there is not a real dependency from the quadrant number.

All the products of the *vmspcaldisp* recipe are shown in Table 7.14.2.

File name	DO category	Type	Explanation
<code>extract_table.fits</code>	EXTRACT_TABLE	FITS	Extraction table
<code>mos_arc_spectrum_extracted.fits</code>	MOS_ARC_SPECTRUM_EXTRACTED	FITS	Extracted slit spectra
<code>MOS_wavecal_grism_q.paf</code>		PAF	Distortion models

Table 7.14.2: *Products of the vmspcaldisp recipe.*

The primary recipe product is the extraction table, that contains information about the local and the global modeling of the spectral distortions. On Table 7.14.3 the meaning of each table column is given (some of the columns are not listed, since they are not used yet). Column Y holds the position of any spectral row (see Figure 8.3.1, page 138) in the produced image of extracted spectra. The  $(x, y)$  mask coordinates matching the  $(X, Y)$  CCD coordinates (as derived by applying the optical distortion model, see Section 8.3.2), corresponding to a point on a slit, are also listed in columns MASK\_X, MASK\_Y, CCD\_X, and CCD\_Y. The “local” curvature model coefficients are extracted from the global curvature solution. In fact, a local curvature model can be computed just where a slit spectrum edge is detected. Currently the column CRVPOL\_RMS is left unused, and in future it will be likely filled just for the first and the last row of each slit spectrum (see Figure 8.3.1, page 138). The local IDS coefficients are not available in case of a failure of the local polynomial fit, as indicated in column DIS\_QUAL.

Column name	Explanation
SLIT	Slit number
Y	Slit row coordinate in image of extracted slit spectra
CCD_X	$X$ position of reference wavelength on CCD
CCD_Y	$Y$ position of reference wavelength on CCD
MASK_X	$x$ mask coordinate along the slit
MASK_Y	$y$ mask coordinate along the slit
SPEC_NO	Number of exposures contributing to this row
CRV_POL_ $i$	$i^{th}$ coefficient of local spatial curvature model
CRVPOL_RMS	RMS of curvature model residuals ( <i>unused</i> )
INV_DIS_ $i$	$i^{th}$ coefficient of local IDS
INVDIS_RMS	RMS of local IDS (CCD pixel)
DIS_QUAL	Quality of local IDS (1 = good, 0 = bad)

Table 7.14.3: *Extraction table entries.*

A secondary product of the *vmspcaldisp* recipe is the image of extracted slit spectra, that allows a visual check of the distortion models quality. Failures of the spatial curvature model would be made apparent by widening dark gaps between the extracted spectra: if the slit spectra edges were followed accurately no gap should be visible at any wavelength. The stability of the wavelength calibration can be evaluated by the alignment of the calibration lamp emission lines from all slits.

A last product is the PAF file carrying all the information related to the spectral distortions. This PAF file is copied (or moved) to the product directory, and it is identical to the IWS configuration file `MOS_wavecal_grism_q.cmf` (where  $q$  indicates the VIMOS quadrant number, and *grism* the grism name) that is created in the directory where *vmspcaldisp* is launched.

The *vmspcaldisp* parameters are listed in table 7.14.4.

A more complete description of the used parameters meaning is given here:

**ApplyFlatField:** If this parameter is set, the flat field correction is applied to the input arc lamp frames. In this case a normalised master flat field must be specified in the input SOF (see table 7.14.1).

**ArcExtraction:** This parameter is used to control the way the image of extracted slit spectra is created. Three different methods are currently available:

**Global:** The slit spectra extraction is performed by applying the improved distortion models computed by the recipe. The global IDS models are applied in the wavelength linearisation.

**Input:** The slit spectra extraction is performed by just applying the “first guess” spectral distortion models that are read from the arc lamp frame header. In this case the *vmspcaldisp* recipe does not try to fit improved distortion models based on the available data (and the output VIMOS IWS configuration file is just a copy of the input “first guess”).

**Local:** The slit spectra extraction is performed by applying the improved distortion models computed by the recipe. The local IDS models are applied in the wavelength linearisation.

Parameter	Possible values	Explanation
ApplyFlatField	true false	Apply flat field correction Do not apply flat field correction
ArcExtraction	Input Local Global	Extract using first guess distortion models Extract using fitted models and local IDS Extract using fitted models and global IDS
BiasMethod	Master Zmaster	Bias removal with no overscan correction Bias removal with overscan correction
CleanBadPixel	true false	Clean bad pixels Do not clean bad pixels
CleanCosmic	true false	Clean cosmic rays Do not clean cosmic rays
ComputeQC	true false	Compute QC parameters Do not compute QC parameters
ExtractionWindow	<i>int</i>	Size of arc line search window (pixel)
Fuzz	<i>int</i> (pixel)	Search radius in spectrum edge detection
ModelSlit	true false	Model wavelength solution within each slit Do not model local IDSs within each slit
ModelSlitOrder	<i>int</i>	Polynomial order for IDS modeling within each slit
RefineIDS	true false	Pretuning of the first guess IDS before line identification Do not use pretuning of the first guess IDS
LineIdent	FirstGuess Blind	Line identification based on first-guess models Line identification based on pattern recognition
LineIdentLevel	<i>float</i>	Threshold for peak detection

Table 7.14.4: *vmspcaldisp* parameters.

**BiasMethod:** Method for bias removal from the input arc lamp exposures. The bias removal procedure is described in some detail in Section 9.3. Possible settings are:

**Master:** After master bias subtraction, prescan and overscan regions are trimmed away from the arc lamp frame.

**Zmaster:** After master bias subtraction the overscan correction is applied before trimming away the overscan regions.

**CleanBadPixel:** Bad pixel correction on the combined arc lamp frame used for optical distortion and inverse dispersion models determination. If this option is turned on, a bad pixel table should be specified in the input SOF (see Table 7.14.1). The bad pixel correction algorithm is described in Section 9.1, page 141.

**CleanCosmic:** Cosmic ray events removal from input arc lamp frames. The cosmic ray rejection algorithm is described in Section 9.2, page 142.

**ComputeQC:** If this parameter is set, QC parameters will be computed and written to the header of the extraction table (see Table 7.14.2) and to an output QC PAF file named `qc0000.paf`. This file is not classified



Parameter	Explanation
QC MOS SLIT WIDTH	Width of slit (mm)
QC MOS HE LAMBDA	He arc lamp line for flux determination (Angstrom)
QC MOS HE FLUX	Flux at chosen He wavelength ( $\text{ADU } mm^{-2} s^{-1}$ )
QC MOS HE FLUXERR	Error on flux at chosen He wavelength ( $\text{ADU } mm^{-2} s^{-1}$ )
QC MOS NE LAMBDA	Ne arc lamp line for flux determination (Angstrom)
QC MOS NE FLUX	Flux at chosen Ne wavelength ( $\text{ADU } mm^{-2} s^{-1}$ )
QC MOS NE FLUXERR	Error on flux at chosen Ne wavelength ( $\text{ADU } mm^{-2} s^{-1}$ )
QC MOS AR LAMBDA	Ar arc lamp line for flux determination (Angstrom)
QC MOS AR FLUX	Flux at reference wavelength ( $\text{ADU } mm^{-2} s^{-1}$ )
QC MOS AR FLUXERR	Error on flux at reference wavelength ( $\text{ADU } mm^{-2} s^{-1}$ )
QC MOS WAVECAL COEFF $i$	Median of IDS coefficient $d_i$ (see Section 8.3.4)
QC MOS REFWAVE MEAN	Mean CCD offset of reference wavelength on all slits (pixel)
QC MOS REFWAVE RMS	RMS of CCD offsets of reference wavelength on all slits (pixel)
QC MOS RESOLUTION1 LAMBDA	Line used in spectral resolution determination (Angstrom)
QC MOS RESOLUTION1	Mean spectral resolution at red end of spectrum
QC MOS RESOLUTION1 RMS	RMS of spectral resolution at red end of spectrum
QC MOS RESOLUTION2 LAMBDA	Line used in spectral resolution determination (Angstrom)
QC MOS RESOLUTION2	Mean spectral resolution at centre of spectrum
QC MOS RESOLUTION2 RMS	RMS of spectral resolution at centre of spectrum
QC MOS RESOLUTION3 LAMBDA	Line used in spectral resolution determination (Angstrom)
QC MOS RESOLUTION3	Mean spectral resolution at blue end of spectrum
QC MOS RESOLUTION3 RMS	RMS of spectral resolution at blue end of spectrum
QC MOS IDS RMS	Global IDS rms (pixel)

Table 7.14.5: *QC parameters of the vmspcaldisp recipe.*

as a pipeline recipe product, as it is an intermediate dataset that in the standard pipeline operations would be translated into new entries in the QC log file.

The QC parameters computed by *vmspcaldisp* are listed in Table 7.14.5. All parameters refer to the slit closest to the mask centre, unless differently specified. Fluxes are determined at the position of a chosen arc lamp line from each working lamp, and they are measured in  $\text{ADU } s^{-1} mm^{-2}$ . The error on fluxes is just the computed theoretical statistical noise. The spectral resolution at different wavelengths is computed as the mean of the resolutions obtained for each spectral row of each slit in the mask (see Figure 8.3.1, page 138). The spectral resolution is computed here as  $\lambda/\Delta\lambda$ , where  $\Delta\lambda$  is the FWHM of the arc lamp line used for the measurement. Finally the RMS of the IDS model, QC MOS IDS RMS, is not derived from the RMSs of the single IDS local polynomial fits, but is computed as the RMS of the deviation of the observed lines peaks on the image of the extracted slit spectra from their expected positions. In this way systematic errors would not be excluded from the computation.

**ExtractionWindow:** Size of the arc line search window on the CCD. The window is centred on an arc lamp line expected position. If a negative value is given, then the search window size is computed by

$$\Delta Y = 3(wb_{01} + 2)$$

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where  $\Delta Y$  is the search window size in CCD pixels,  $w$  is the slit width in millimetres, and  $b_{01}$  is the conversion factor between millimetres on the mask and pixels on the CCD along the dispersion direction, obtained from the optical distortion model (see Table 8.3.1, page 136).

**Fuzz:** Search radius for spectral edges, used in the determination of the spatial curvature model based on the input combined flat field. See Section 9.24, page 9.24, for more details.

**LineIdent:** Arc lines identification method. The identification procedure is described in some detail in Section 9.24.4. Possible settings are:

**Blind:** Arc lamp lines are identified without making use of the first-guess IDS models from the headers of the input files. This method, based on pattern recognition, just requires the rough estimate of the expected spectral dispersion read from the input grism table. Choosing this option could be the last resort in the attempt to calibrate data that are associated with very inaccurate first-guess distortion models.

**FirstGuess:** Arc lamp lines are identified on the basis of existing models of the spectral distortions, used as first-guesses. Inaccurate models might be “tuned” by setting the parameter *RefineIDS*, or trying larger values for the parameters *ExtractionWindow* and/or *Fuzz*. If all this fails, then it may help to apply the newly available *Blind* line identification method.

**LineIdentLevel:** Any signal that is peaking above this threshold is taken as a candidate arc lamp line to be identified by the *Blind* pattern recognition method. The *LineIdentLevel* is measured relatively to the local background level. If the chosen line identification method is not set to *Blind*, this parameter has no effect.

For optimal results with the *Blind* line identification method, it may be required to conveniently adapt the line identification level to the peak value of the faintest lines in the arc lamp exposure, but not to the extent of picking up too much of the background noise. On the other side, setting a too high value for *LineIdentLevel* may cause the loss of a number of valid arc lamp lines, leaving the *Blind* method with no recognisable pattern to match. Note that, as a rule, it is advisable to have more arc lamp lines candidates than lines actually listed in the input line catalog.

**ModelSlit:** The trend of the local IDS coefficients within a single slit can be modeled by a polynomial fit. This may reduce the effect of outlying local solutions, before the global IDS fit is tried.

**ModelSlitOrder:** The order of the polynomial used in the slit IDS modeling when *ModelSlit* is set.

**RefineIDS:** When this parameter is set, the “first guess” IDS polynomial valid for a given spectral row is slightly modified, searching for a best match of the catalog wavelengths with the local spectrum arc lines. This pretuning operation permits a more robust arc lamp lines identification, but it should be avoided in presence of severe light contamination from reflections and/or spectral orders overlap (see Figure 7.14.1).

A description of the algorithms used in this recipe is given in Section 9.24, page 158.

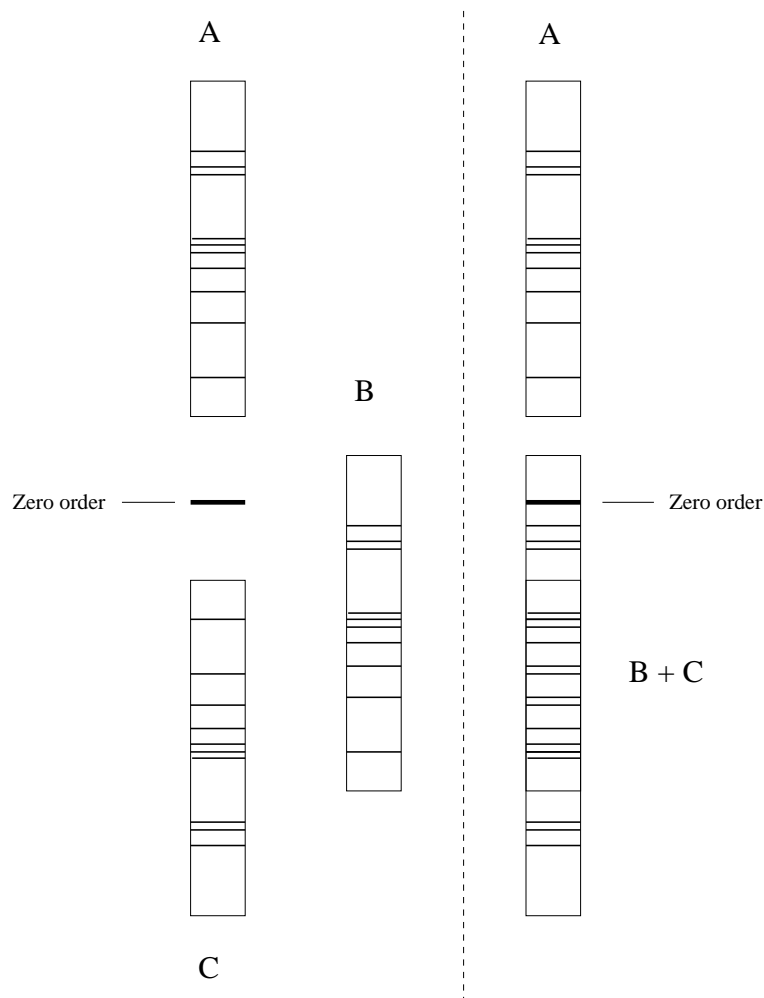


Figure 7.14.1: Contamination from orders 0 and -1 in multiplexed spectra. On the left, the first order slit spectra A and B are shown, together with the 0 and the -1 orders of spectrum A. If spectra A and B are multiplexed, as shown on the right, spectrum B is contaminated by the 0 and -1 orders of spectrum A.

## 7.15 vmmosobsstare

The VIMOS pipeline recipe *vmmosobsstare* is used to apply basic reduction steps to one exposure made in MOS mode, to locate objects, and to optimally extract and flux calibrate their spectra.

The files to be included in the input SOF are listed in Table 7.15.1.

DO category	Type	Explanation	Required
MOS_SCIENCE	Raw frame	Science exposure	✓
MASTER_BIAS	Calibration	Master bias	✓
MASTER_DARK	Calibration	Master dark	
MOS_MASTER_SCREEN_FLAT	Calibration	Normalised flat field	
EXTRACT_TABLE	Calibration	Extraction table	
GRISM_TABLE	Calibration	Grism table	✓
EXTINCT_TABLE	Calibration	Atmospheric extinction table	
MOS_SPECPHOT_TABLE	Calibration	Spectro-photometric table	
CCD_TABLE	Calibration	Bad pixel table	

Table 7.15.1: *Input files for the vmmosobsstare recipe.*

The bad pixel table needs to be specified only if the cleaning of bad pixels is requested. In the calibration directories there is one CCD\_TABLE file for each quadrant, named *badpixel.q.tfits* (where *q* is the quadrant number increased by 4). Care should be taken in selecting the appropriate bad pixel tables for the spectral instrument modes (in the case of imaging data *q* is the quadrant number).

A flat field correction is applied only if a normalised master flat field (produced by the recipe *vmsspflat*) is specified.

The extraction table is the product of the local spectral distortions modeling performed by the recipe *vmspcaldisp* (see table 7.14.3, page 103). If an extraction table is not specified, then the global distortion models read from the science frame header are used (see Section 8.3, pages 135-140).

If a flux calibration is requested, a spectro-photometric table produced by the recipe *vmmosstandard* must be specified together with an atmospheric extinction table (see Tables 7.18.2 on page 118, and 7.18.6 on page 120). Note that a flux calibration can also be applied to the reduced data at a later stage, using the recipe *vmsspphot* (see Section 7.23, page 130).

The grism table contains necessary information to control the way spectra are extracted, starting from the reference wavelength (header entry PRO WLEN CEN), on a specific range of pixels above and below its position on the CCD (header entries PRO SPECT LLEN LO and PRO SPECT LLEN HI) (see Figure 8.3.1, page 138). Other parameters, used in the extraction of the science slit spectra (see Table 7.15.2), are the start and the end wavelength of the image of the extracted slit spectra (header entries PRO WLEN START and PRO WLEN END), and the step of the sampling along the dispersion direction (header entry PRO WLEN INC). Finally, the wavelengths of the sky lines used in the alignment of the spectral distortion models, necessary to keep into account the possible coordinates shifts introduced by a variation of the instrument flexures between the science and the calibration exposures, are listed in the header keywords PRO SKY WLEN $n$ , with  $n$  ranging from 1 to the number specified in the keyword PRO SKY NO. In the calibration directories there is one GRISM\_TABLE file for each quadrant/grism combination, named *grs\_grism.q.tfits* (where *grism* is the grism name,

and  $q$  is the quadrant number).

All the products of the `vmmosobsstare` recipe are shown in Table 7.15.2.

File name	DO category	Type	Explanation
mos_science_reduced.fits	MOS_SCIENCE_REDUCED	FITS	Objects spectra
mos_science_flux_reduced.fits	MOS_SCIENCE_FLUX_REDUCED	FITS	Flux calibrated objects spectra
mos_science_extracted.fits	MOS_SCIENCE_EXTRACTED	FITS	Sky subtracted slit spectra
mos_science_sky.fits	MOS_SCIENCE_SKY	FITS	Sky spectra
mos_sky_reduced.fits	MOS_SKY_REDUCED	FITS	Extracted sky spectra
object_table.fits	OBJECT_TABLE	FITS	Objects spectra identification
window_table.fits	WINDOW_TABLE	FITS	Objects positions in slit

Table 7.15.2: *Product of the vmmosobsstare recipe.*

The slit spectra are remapped with the instrument distortions removed and at a fixed wavelength step. A sky value is estimated for each wavelength and then subtracted from the data. The result is stored in the MOS\_SCIENCE\_EXTRACTED image, while the images MOS\_SCIENCE\_SKY and MOS\_SKY\_REDUCED contain the sky model that was subtracted from the resampled data.

If a flux calibration is requested, then a MOS\_SCIENCE\_FLUX\_REDUCED image is also created. This image is identical to the MOS\_SCIENCE\_REDUCED one, but the spectra it contains are flux calibrated, and expressed in units of  $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ . Note, however, that the obtained fluxes are valid except for a constant factor: the applied calibration is relative, not absolute.

The positions of the extracted slit spectra and of the detected objects they may contain are listed in the window table, 7.15.3.

Column name	Explanation
SLIT	Slit number in ADM
SPEC_LEN	<i>unused</i>
SPEC_START	Image bottom row of slit spectrum (pixel)
SPEC_END	Image top row of slit spectrum (pixel)
OBJ_START	Object start position from slit spectrum bottom (pixel)
OBJ_END	Object end position from slit spectrum bottom (pixel)
OBJ_NO	Object counter within a slit
OBJ_POS	Object peak position from slit spectrum bottom (pixel)
OBJ_WIDTH	<i>unused</i>
OBJ_X	Mask $x$ coordinate of object (mm)
OBJ_Y	Mask $y$ coordinate of object (mm)
OBJ_RA	<i>unused</i>
OBJ_DEC	<i>unused</i>

Table 7.15.3: *Window table entries. The IFU entries are not listed, because IFU data reduction is not yet supported. The positions of the slit spectra are counted from the image bottom (with the first row at  $Y = 0$ ), while the objects positions are counted from the bottom row of the slit to which they belong.*

The extracted spectra of the detected objects are stored in the rows of the `MOS_SCIENCE_REDUCED` image, that is the primary product of this recipe. The object table, shown in Table 7.15.4, indicates from what slit each spectrum was extracted.

Column name	Explanation
SLIT	Slit number in ADM
Y	Image row of extracted spectrum
OBJ_NO	Object counter within same slit
OBJ_X	Mask $x$ coordinate of object
OBJ_Y	Mask $y$ coordinate of object
OBJ_RA	<i>unused</i>
OBJ_DEC	<i>unused</i>

Table 7.15.4: *Object table entries. The  $Y$  pixel positions of the extracted spectra are counted from the image bottom, with the first row at  $Y = 0$ .*

The `vmmosobsstare` parameters are listed in Table 7.15.5.

A more complete description of the used parameters meaning is given here:

**BiasMethod:** Method for bias removal from the input science exposure. The bias removal procedure is described in some detail in Section 9.3. Possible settings are:

**Master:** After master bias subtraction, prescan and overscan regions are trimmed away from the science frame.

**Zmaster:** After master bias subtraction the overscan correction is applied before trimming away the overscan regions.

**CalibrateFlux:** Flux calibration of the extracted spectra. If this option is turned on, an atmospheric extinction table and a spectro-photometric table (see tables 7.18.2 and 7.18.6, pages 118 and 120) should be specified in the input SOF. The flux calibration is applied as described in Section 9.10, page 147.

**CleanBadPixel:** Bad pixel correction on the input science frame. If this option is turned on, a bad pixel table should be specified in the input SOF (see table 7.15.1). The bad pixel correction algorithm is described in Section 9.1, page 141.

**DetectionLevel:** In the object detection task, only the pixel values that are *DetectionLevel* noise sigmas above the background level are included in the objects candidates. The object detection is tried on the mean cross-dispersion profile of the extracted slit spectra. The mean profile is computed on the wavelength interval specified by the grism table entries `PRO AVG POS` and `PRO AVG RNG`.

**Fuzz:** Extra number of  $X$  CCD pixels, to be added at the slit spectra sides during the slit spectra extraction as a safety margin.

Parameter	Possible values	Explanation
BiasMethod	Master Zmaster	Bias removal with no overscan correction Bias removal with overscan correction
CleanBadPixel	true false	Clean bad pixels Do not clean bad pixels
ModelSlit	true false	Model global IDS within each slit Apply wavelength solution from extraction table
ModelSlitOrder	<i>int</i>	Polynomial order for global IDS within each slit
UseSkylines	true false	Use sky lines to align wavelength calibration Do not align wavelength calibration
SkyMethod	Median Fit	Sky at object position is median of all sky values Sky at object position is interpolation of sky values
PolyOrder	<i>int</i>	Order of sky interpolating polynomial
SkyKSigmaLow	<i>float</i> (sigma)	Low limit for K-sigma clipping in sky fitting
SkyKSigmaHigh	<i>float</i> (sigma)	High limit for K-sigma clipping in sky fitting
Fuzz	<i>int</i> (pixel)	Extra $X$ pixels in slit spectra extraction
SlitMargin	<i>int</i> (pixel)	Excluded pixels at slit ends for sky determination
LineWidth	<i>int</i> (pixel)	Pixels to read around expected sky line position
DetectionLevel	<i>float</i> (sigma)	Object detection level in terms of noise sigmas
WatershedLevels	<i>int</i>	No. of levels in watershed method for objects unblending
WatershedFraction	<i>float</i>	Minimum flux fraction of unblended objects
MinObjectSize	<i>int</i> (pixel)	Minimum allowed object size
MaxObjectSize	<i>int</i> (pixel)	Minimum interval where to attempt objects unblending
HorneExtraction	true false	Optimal (Horne's) spectral extraction Aperture spectral extraction
CalibrateFlux	true false	Apply flux calibration to extracted spectra Do not apply flux calibration

Table 7.15.5: *vmmosobsstare* parameters.

**HorneExtraction:** If this parameter is set, the Horne's method for spectral optimal extraction (K.Horne (1986), PASP 98, p.609) is applied to the objects detected in the extracted slit spectra.<sup>13</sup> Otherwise a simple aperture extraction is used.

**LineWidth:** Search radius (in pixels along the dispersion direction) from the expected position of the sky lines in the input science frame. This parameter is only effective when *UseSkylines* is set.

**MaxObjectSize:** In the object detection process, all the pixel values of the slit mean cross-dispersion profile that are above the threshold specified at *DetectionLevel* are selected. If any unbroken sequence of selected pixels is longer than *MaxObjectSize*, an attempt to unblend it into sub-objects is made.

**MinObjectSize:** In the object detection process, all the pixel values of the slit mean cross-dispersion profile that are above the threshold specified at *DetectionLevel* are selected. Any unbroken sequence of selected pixels must be at least *MinObjectSize* pixels long to be accepted as an object candidate.

<sup>13</sup>To be rigorous, Horne's extraction is not intended to be applied to resampled data, where the noise is correlated.

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**ModelSlit:** If this parameter is set, and an extraction table is specified in input, the coefficients of the local IDS solutions contained in the extraction table (see Table 7.14.3, page 103) are modeled within each slit by a polynomial fit. The model values for the coefficients are replaced in the extraction table and then used in the spectral extraction process. This is a way to smooth out outlying IDS local solutions.

**ModelSlitOrder:** This parameter is only effective when *ModelSlit* is set and an extraction table is specified in input. The order of the polynomial used in the global IDS solutions within each slit is specified. In particular, if this parameter is set to zero the local IDS coefficients are replaced by their mean values within each slit.

**PolyOrder:** Order of the polynomial used in sky level modeling, when *SkyMethod* is set to *Fit*.

**SkyKSigmaLow:** Low threshold for K-sigma clipping in sky level modeling, when *SkyMethod* is set to *Fit*.

**SkyKSigmaHigh:** High threshold for K-sigma clipping in sky level modeling, when *SkyMethod* is set to *Fit*.

**SkyMethod:** Method used for the sky determination at the position of the detected objects. The sky level is determined for each sampled wavelength of the extracted slit spectra. The modeled slit sky spectra are written to the output `MOS_SCIENCE_SKY` image. Possible settings are:

**Fit:** The pixel values outside the regions where objects were detected are fitted by a polynomial. The model values are then taken as the sky level. The order of the polynomial used is specified at the parameter *PolyOrder*.

**Median:** The median of the pixel values outside the regions where objects were detected is taken as the sky level.

**SlitMargin:** Number of pixels at the edges of the extracted slit spectra, to be excluded from the determination of the sky level and from the object detection task.

**UseSkylines:** If this parameter is set, the sky lines listed in the grism table are searched and identified in the input science exposure. The median offset from their expected positions along the dispersion direction is taken as a measure of the variation of the instrument flexure between the science exposure and the flat field and arc lamp exposures used for calibration. This offset is added to the *Y* component of the optical distortion model (see Section 8.3.2, page 136) before its usage in the spectral extraction task.

**WatershedFraction:** In the object detection process, an attempt of unblending into sub-objects an extended (*i.e.*, greater than *MaxObjectSize*) object candidate is made. A candidate sub-object must have at least the fraction of the total flux specified here, in order to be flagged as a separate object.

**WatershedLevels:** Number of levels used in watershed method applied to object unblending. See parameter *MaxObjectSize* about object unblending.

A description of the algorithms used in this recipe is given in Section 9.25, page 173.



## 7.16 vmmosobsjitter

The VIMOS pipeline recipe *vmmosobsjitter* is used to apply basic reduction steps to a sequence of exposures made in MOS mode, to combine them in a single image, to locate objects, and to optimally extract and possibly flux calibrate their spectra. Sky fringes may also be subtracted if requested. Each input image is processed in the same way as by recipe *vmmosobsstare*, therefore what mainly characterises the *vmmosobsjitter* recipe is the combination of the input frames, and the sky fringes subtraction.

The files to be included in the input SOF are listed in Table 7.16.1.

DO category	Type	Explanation	Required
MOS_SCIENCE	Raw frame	Science exposures	✓
MASTER_BIAS	Calibration	Master bias	✓
MASTER_DARK	Calibration	Master dark	
MOS_MASTER_SCREEN_FLAT	Calibration	Normalised flat field	
EXTRACT_TABLE	Calibration	Extraction table	
GRISM_TABLE	Calibration	Grism table	✓
MOS_FRINGES_SKY	Calibration	Sky+fringes map	
MOS_FRINGES	Calibration	Fringe map	
EXTINCT_TABLE	Calibration	Atmospheric extinction table	
MOS_SPECPHOT_TABLE	Calibration	Spectro-photometric table	
CCD_TABLE	Calibration	Bad pixel table	

Table 7.16.1: *Input files for the vmmosobsjitter recipe.*

Most of the entries in Table 7.16.1 are described in Section 7.15, page 108, being in common with the recipe *vmmosobsstare*. In addition to those, the *vmmosobsjitter* recipe also accepts either a *sky+fringes map* or a *fringe map* (not both), depending on the selected sky fringing removal method. These maps are typically produced by previous runs of the *vmmosobsjitter* recipe where no input fringe map was specified.

It should be noted that such maps are never required in input: when the sky fringing correction is requested, they are automatically produced by median-stacking the input jittered frames themselves. However, in some cases it may turn appropriate to generate a sky fringes map that is based on just a subset of exposures (*e.g.*, those that are separated by a wider jittering step). Running the recipe on this subset would produce a sky fringes map that may then be applied on further recipe runs to the whole set of jittered exposures. In fact, when a sky fringes map is specified in input it is not recomputed by the recipe, but it is just applied to the data according to the specified correction method (see the parameters description ahead, and Section 9.8, page 145 for more details).

All the products of the *vmmosobsjitter* recipe are shown in Table 7.16.2. The only extra entries with respect to the *vmmosobsstare* recipe are the fringes maps, that are a by-product of the sky fringing correction.

The *vmmosobsjitter* configuration file includes the same parameters of recipe *vmmosobsstare*, shown in table 7.15.5, page 111, with few more parameters related to spectral stacking and sky fringes removal, that are described in table 7.16.3.

A more complete description of these extra parameters is given here:

**FringingCorr:** Sky fringing removal from product frame. If this parameter is set, an input fringe map may

File name	DO category	Type	Explanation
mos_science_reduced.fits	MOS_SCIENCE_REDUCED	FITS	Objects spectra
mos_science_flux_reduced.fits	MOS_SCIENCE_FLUX_REDUCED	FITS	Flux calibrated spectra
mos_science_extracted.fits	MOS_SCIENCE_EXTRACTED	FITS	Sky subtracted slit spectra
mos_science_sky.fits	MOS_SCIENCE_SKY	FITS	Sky spectra
mos_sky_reduced.fits	MOS_SKY_REDUCED	FITS	Extracted sky spectra
object_table.fits	OBJECT_TABLE	FITS	Objects spectra identification
window_table.fits	WINDOW_TABLE	FITS	Objects positions in slit
mos_fringes_sky.fits	MOS_FRINGES_SKY	FITS	Sky+fringes map ('Raw')
mos_fringes.fits	MOS_FRINGES	FITS	Fringe map ('Resampled')

Table 7.16.2: *Product of the vmmosobsjitter recipe.*

be specified in order to subtract it from the input spectral exposures before combining them. If no input fringe map is given, the fringe map is derived from all the input jittered spectral exposures.

**FringingMethod:** Method used for the determination and the removal of the sky fringes. Possible settings are:

**Raw:** The used sky+fringe map (DO category MOS\_FRINGES\_SKY) is the median stacking of a set of jittered *raw* and bias subtracted spectral frames. This image, containing both fringes and mean sky level, is subtracted from each input *raw* and bias subtracted spectral frame. After that, the data reduction proceeds in the usual way: in particular, residuals due to sky changing between exposures are eliminated by the standard sky removal procedure controlled by the parameter *SkyMethod* (see Table 7.15.5, page 111). If no sky+fringe map is given in input, a sky+fringe map is generated by median-stacking all the input *raw* and bias subtracted spectral frames.

**Resampled:** The used fringe map (DO category MOS\_FRINGES) is the median stacking of a set of jittered spectral frames, after the signal *resampling* (applied to eliminate all the spectral distortions including the wavelength calibration), and after the subtraction of the sky with the method specified by *SkyMethod*. If no fringe map is given in input, a fringe map is generated by median-stacking all the processed and *resampled* spectral frames.

**FringingOffset:** Minimum offset (in pixel) between any two jittered exposure, required for applying the fringing correction. If at least two jittered frames differ by an offset smaller than the one specified here, then the fringing correction is not applied even if it was requested by setting the parameter *FringingCorr*.

**KSigmaHigh:** Number of standard deviations above the median pixel value for rejecting a pixel value when *StackMethod* is set to "*Ksigma*".

**KSigmaLow:** Number of standard deviations below the median pixel value for rejecting a pixel value when *StackMethod* is set to "*Ksigma*".

**MaxRejection:** Number of highest pixel values to be rejected when *StackMethod* is set to "*MinMax*".

**MinRejection:** Number of lowest pixel values to be rejected when *StackMethod* is set to "*MinMax*".

**SaveIntermediate:** When this is set, intermediate products of the data reduction are saved to disk. This would allow the user to better evaluate the quality of the results at each step of the reduction algorithm. The data

Parameter	Possible values	Explanation
StackMethod	Average	Average combination of reduced slit spectra
	Median	Median combination of reduced slit spectra
	MinMax	Min-max combination of reduced slit spectra
	Ksigma	K-sigma clipping combination of reduced slit spectra
	Auto	Optimal combination of reduced slit spectra
KSigmaLow	<i>float</i> (sigma)	Low threshold for K-sigma clipping method
KSigmaHigh	<i>float</i> (sigma)	High threshold for K-sigma clipping method
MaxRejection	<i>int</i>	Number of highest values excluded in rejection stack method
MinRejection	<i>int</i>	Number of lowest values excluded in rejection stack method
FringingCorr	true	Remove sky fringing
	false	Do not remove sky fringing
FringingMethod	Raw	Remove sky+fringes from raw spectra
	Resampled	Remove fringes from reduced spectra
FringingOffset	<i>float</i> (pixel)	Smallest required offset between exposures
SaveIntermediate	true	Save intermediate products
	false	Do not save intermediate products

Table 7.16.3: *vmmosobsstare* parameters.

that are created on disk are not officially products of the pipeline, being just a debug aid, and nothing more: for this reason they will not be reported by the recipe launcher *esorex*, or by *Gasgano*. The intermediate products will be created in the current working directory, and they will always have the same names, conventionally beginning with the word `after_`, prefixing an identifier of a specific data reduction step, and an index indicating a given input frame. For instance, the file `after_bias_subtraction3.fits` contains the third input jittered frame after the master bias subtraction.

**StackMethod:** Method used for combination of the reduced slit spectra. See Section 9.6 for a complete description of all the combination methods. Possible settings are:

**Auto:** Given the number of input jittered spectral exposures, an optimal combination method is selected. Currently this is always going to the method “*Average*”.

**Average:** The combined frame is the mean of the reduced and aligned input spectral exposures.

**Ksigma:** The combined frame is the mean of the reduced and aligned input spectral exposures, after K-sigma screening of pixel values. The number of sigma to be applied in the rejection is specified by the parameters *KSigmaLow* and *KSigmaHigh*.

**Median:** The combined frame is the median of the reduced and aligned input spectral exposures.

**MinMax:** The combined frame is the mean of the reduced and aligned input spectral exposures, after rejection of minimum and maximum values. The number of values to reject is specified by the parameters *MinRejection* and *MaxRejection*.

A description of the algorithms used in this recipe is given in Section 9.26, page 174.

## 7.17 vmmoscombine

With this recipe the reduced spectra from different observations (obtained, for instance, during different nights) may be aligned and combined together, provided that they were observed with the same mask, with the same instrument quadrant, and with the same instrument mode.

The available stacking methods are those provided by the recipe *vmmosobsjitter* (see Section 7.16, page 113), and they are applied to the 2D-extracted spectra (MOS\_SCIENCE\_EXTRACTED) produced by the recipes *vmmosobsstare*, *vmmosobsjitter*, and even by the recipe *vmmoscombine* itself. Before being stacked, the spectra are all corrected to airmass zero, and normalised to their mean exposure time. The value of the mean exposure time is written to the products' header keyword `EXPTIME` (the actual exposure time is stored in the header keyword `ESO PRO EXPTTOT`).

After the stacking of the slit spectra, the object detection task is run and the spectra of the detected objects are 1D-extracted as is done by the recipes *vmmosobsstare* and *vmmosobsjitter*: note, however, that in this case no optimal spectral extraction is applicable.

Only in case any input `MOS_SCIENCE_EXTRACTED` frame was produced by the recipe *vmmosobsstare*, the matching `WINDOW_TABLE` produced in the same run must be included in the input set-of-frame.

Optionally, a relative flux correction may also be applied, and in that case a spectro-photometric table must be specified in the input set-of-frames. An atmospheric extinction table must be specified in any case, even if a flux correction was not requested, because of the necessary correction to airmass zero before the stacking of the spectra.

The tables describing all the input and product frames, with the recipe's configuration parameters, are self-explaining:

DO category	Type	Explanation	Required
MOS_SCIENCE_EXTRACTED	Product frame	Reduced slit spectra	✓
GRISM_TABLE	Calibration	Grism table	✓
WINDOW_TABLE	Calibration	Window table	See text
EXTINCT_TABLE	Calibration	Atmospheric extinction table	✓
MOS_SPECPHOT_TABLE	Calibration	Spectro-photometric table	

Table 7.17.1: *Input files for the vmmoscombine recipe.*

File name	DO category	Type	Explanation
mos_science_reduced.fits	MOS_SCIENCE_REDUCED	FITS	Objects spectra
mos_science_flux_reduced.fits	MOS_SCIENCE_FLUX_REDUCED	FITS	Flux calibrated spectra
mos_science_extracted.fits	MOS_SCIENCE_EXTRACTED	FITS	Stacked slit spectra
object_table.fits	OBJECT_TABLE	FITS	Objects spectra identification
window_table.fits	WINDOW_TABLE	FITS	Objects positions in slit

Table 7.17.2: *Product of the vmmoscombine recipe.*

Parameter	Possible values	Explanation
StackMethod	Average	Average combination of reduced slit spectra
	Median	Median combination of reduced slit spectra
	MinMax	Min-max combination of reduced slit spectra
	Ksigma	K-sigma clipping combination of reduced slit spectra
	Auto	Optimal combination of reduced slit spectra
KSigmaLow	<i>float</i> (sigma)	Low threshold for K-sigma clipping method
KSigmaHigh	<i>float</i> (sigma)	High threshold for K-sigma clipping method
MaxRejection	<i>int</i>	Number of highest values excluded in rejection stack method
MinRejection	<i>int</i>	Number of lowest values excluded in rejection stack method
DetectionLevel	<i>float</i> (sigma)	Object detection level in terms of noise sigmas
WatershedLevels	<i>int</i>	No. of levels in watershed method for objects unblending
WatershedFraction	<i>float</i>	Minimum flux fraction of unblended objects
MinObjectSize	<i>int</i> (pixel)	Minimum allowed object size
MaxObjectSize	<i>int</i> (pixel)	Minimum interval where to attempt objects unblending
CalibrateFlux	true	Apply flux calibration to extracted spectra
	false	Do not apply flux calibration

Table 7.17.3: *vmmoscombine* parameters.

## 7.18 vmmosstandard

The VIMOS pipeline recipe *vmmosstandard* is used to calibrate and extract a spectrum from a MOS exposure of a spectro-photometric standard star, and derive the instrument efficiency and the response curves by comparison with the corresponding catalog spectrum.

The files to be included in the input SOF are listed in Table 7.18.1.

DO category	Type	Explanation	Required
MOS_STANDARD	Raw frame	Standard star exposure	✓
MASTER_BIAS	Calibration	Master bias	✓
MASTER_DARK	Calibration	Master dark	
EXTINCT_TABLE	Calibration	Atmospheric extinction table	✓
STD_FLUX_TABLE	Calibration	Spectro-photometric table	✓
MOS_MASTER_SCREEN_FLAT	Calibration	Normalised flat field	
EXTRACT_TABLE	Calibration	Extraction table	
GRISM_TABLE	Calibration	Grism table	✓
CCD_TABLE	Calibration	Bad pixel table	

Table 7.18.1: *Input files for the vmmosstandard recipe.*

An atmospheric extinction table must be specified (see Table 7.18.2). Currently the atmospheric extinction table valid for La Silla is made available in the calibration directories, in a file named `extinct_table.fits`.

The catalog fluxes for the observed standard star are contained in the standard star flux table (see Table 7.18.3).

Column name	Explanation
WAVE	Wavelength at which the extinction was evaluated
EXTINCTION	Magnitude loss per one airmass

Table 7.18.2: *Atmospheric extinction table entries.*

Column name	Explanation
WAVE	Wavelength at which the flux was evaluated
FLUX	Flux in $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$
BIN	Bin width in $\text{\AA}$ strom

Table 7.18.3: *Standard star flux table.*

A set of standard star flux tables, corresponding to the 30 spectro-photometric standard stars that are included in the VIMOS calibration plan ([8]), is available in the calibration directories. The names of these tables, and the name of the standard stars as reported in the FITS header keyword `ESO OBS TARG NAME`, are listed in Table 7.18.4. The table indicated in the SOF should match the content of the header entry `ESO OBS TARG NAME` of the input standard star exposure.

The bad pixel table needs to be specified only if the cleaning of bad pixels is requested. In the calibration directories there is one `CCD_TABLE` file for each quadrant, named `badpixel.q.tfits` (where  $q$  is the quadrant number increased by 4). Care should be taken in selecting the appropriate bad pixel tables for the spectral instrument modes (in the case of imaging data  $q$  is the quadrant number).

The extraction table is the product of the local spectral distortions modeling performed by the recipe `vmcpcaldisp` (see table 7.14.3, page 103). If an extraction table is not specified, then the global distortion models read from the science frame header are used (see Section 8.3, pages 135-140).

A flat field correction is applied only if a normalised master flat field (produced by the recipe `vmcspflat`) is specified.

The grism table contains necessary information to control the way spectra are extracted, as described in more detail in section 7.15, page 108. In the calibration directories there is one `GRISM_TABLE` file for each quadrant/grism combination, named `grs_grism.q.tfits` (where *grism* is the grism name, and  $q$  is the quadrant number).

All the products of the `vmmosstandard` recipe are shown in Table 7.18.5.

The standard star spectrum is calibrated and extracted as in recipe `vmmosobsstare`. Next, the extracted spectrum is compared to catalog fluxes of the same star to obtain the efficiency curve and the response curve used for the flux calibration of scientific data (see Section 9.9, page 146).

The result MOS spectro-photometric table is shown in Table 7.18.6.

File name	Target name	Catalog
bd25d4655.tfits	BD+25d4655	Oke (1990)
bd28d4211.tfits	BD+28d4211	Oke (1990)
bd33d2642.tfits	BD+33d2642	Oke (1990)
cd32d9927.tfits	CD-32-9927	Hamuy et al. (1992, 1994)
eg21.tfits	EG-21	Hamuy et al. (1992, 1994)
eg274.tfits	EG-274	Hamuy et al. (1992, 1994)
feige110.tfits	Feige-110	Hamuy et al. (1992, 1994)
feige56.tfits	Feige-56	Hamuy et al. (1992, 1994)
feige66.tfits	Feige-66	Oke (1990)
feige67.tfits	Feige-67	Oke (1990)
g158_100.tfits	G-158-100	Oke (1990)
g93_48.tfits	G-93-48	Oke (unpublished) data
gd108.tfits	GD-108	Oke (1990)
gd50.tfits	GD-50	Oke (1990)
hilt600.tfits	Hiltner-600	Hamuy et al. (1992, 1994)
hz2.tfits	Hz-2	Oke (unpublished) data
hz44.tfits	Hz-44	Oke (1990)
lds749b.tfits	LDS-749b	Oke (1990)
ltd1020.tfits	LTT-1020	Hamuy et al. (1992, 1994)
ltd1788.tfits	LTT-1788	Hamuy et al. (1992, 1994)
ltd2415.tfits	LTT-2415	Hamuy et al. (1992, 1994)
ltd377.tfits	LTT-377	Hamuy et al. (1992, 1994)
ltd3864.tfits	LTT-3864	Hamuy et al. (1992, 1994)
ltd4816.tfits	LTT-4816	Hamuy et al. (1992, 1994)
ltd6248.tfits	LTT-6248	Hamuy et al. (1992, 1994)
ltd7379.tfits	LTT-7379	Hamuy et al. (1992, 1994)
ltd7987.tfits	LTT-7987	Hamuy et al. (1992, 1994)
ltd9239.tfits	LTT-9239	Hamuy et al. (1992, 1994)
ltd9491.tfits	LTT-9491	Hamuy et al. (1992, 1994)
ngc7293.tfits	NGC-7293	Oke (1990)

Table 7.18.4: *Spectro-photometric standard stars in the VIMOS Calibration Plan. Full references are: Oke, 1990, AJ 99, 1621; Hamuy et al., 1992, PASP 104, 533; Hamuy et al., 1994, PASP 106, 566. See also <http://www.eso.org/observing/standards/spectra/>*

File name	DO category	Type	Explanation
mos_standard_reduced.fits	MOS_STANDARD_REDUCED	FITS	Extracted spectrum
mos_standard_extracted.fits	MOS_STANDARD_EXTRACTED	FITS	Sky subtr. slit spectra
mos_standard_sky.fits	MOS_STANDARD_SKY	FITS	Sky slit spectra
mos_standard_sky_extracted.fits	MOS_STANDARD_SKY_EXTRACTED	FITS	Extracted sky spectrum
mos_specphot_table.fits	MOS_SPECPHOT_TABLE	FITS	Response curves
object_table.fits	OBJECT_TABLE	FITS	Object identification
window_table.fits	WINDOW_TABLE	FITS	Object position in slit

Table 7.18.5: *Product of the vmmosstandard recipe.*

Column name	Explanation
WAVE	Wavelength in Ångstrom
STD_FLUX	Standard star flux in $\text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$
OBS_FLUX	Observed flux in $e^{-} \text{s}^{-1} \text{Å}^{-1}$
RAW_EFFICIENCY	Ratio between input and detected photons
EFFICIENCY	Heavily smoothed version of RAW_EFFICIENCY
RAW_RESPONSE	Ratio between STD_FLUX and OBS_FLUX
RESPONSE	Heavily smoothed version of RAW_RESPONSE

Table 7.18.6: *Spectro-photometric table.*

Most of the *vmmosstandard* parameters are the same as for recipe *vmmosobsstare* (see Table 7.15.5, page 111). The parameter *DetectionLevel* is set as a default to a very high value, so that in general just one spectrum will be unambiguously detected and identified as the standard star one. In case more than one object is detected, it may be appropriate to increase this value, or even to modify the object detection parameters *MinObjectSize*, *MaxObjectSize*, or *WatershedFraction*. Alternatively, the parameter *SelectSlit* may be used to indicate in what slit the standard star is really located: normally this parameter is set to zero, meaning that objects are searched in all slits, but a positive number would limit the search to just the specified slit.

The parameter *ComputeQC* is typically set for monitoring the instrument efficiency at specific wavelengths.

A description of the algorithms used in this recipe is given in Section 9.27, page 175.

## 7.19 vmifucalib

The VIMOS pipeline recipe *vmifucalib* is used to determine the spatial extraction mask, the wavelength calibration, and the fibers relative transmission correction, from a set of flat field and one arc lamp exposures.

The files to be included in the input SOF are listed in Table 7.19.1.

At least one flat field exposure should be present in the input SOF, but if an arc lamp exposure is not given, then only the spatial extraction mask can be determined.

If an arc lamp exposure is given in input, a line catalog must also be provided.



DO category	Type	Explanation	Required
IFU_SCREEN_FLAT	Raw frame	Flat field exposure	✓
IFU_ARC_SPECTRUM	Raw frame	Arc lamp exposure	
MASTER_BIAS	Calibration	Master bias	✓
LINE_CATALOG	Calibration	Line catalog	
IFU_IDENT	Calibration	Fiber identification	
CCD_TABLE	Calibration	Bad pixel table	

Table 7.19.1: *Input files for the vmifucalib recipe.*

The fiber identification file is optional: it consists of intensity profiles (one for each IFU pseudo-slit) cut along the cross-dispersion direction of a reference flat field exposure where the fiber spectra have been safely identified. The fibers corresponding to the peak positions of each profile are listed in the tables included in the FITS file extensions. Such safe identifications would then be transferred to the new input flat fields by cross-correlation. In the calibration directories there is ideally one IFU\_IDENT file for each quadrant/grism combination, named *ifu\_ident\_grism\_q.fits* (where *q* indicates the VIMOS quadrant number, and *grism* the grism name). A new set of fiber identification files has been recently added, in order to support IFU data obtained around 2006 and after. In order to differentiate them from the earlier IFU\_IDENT files the suffix "\_2006" was added to their names.

If a fiber identification file is not specified, the fiber spectra identification is still attempted, but the result is not always correct. A fiber misidentification would appear later on the reconstructed image of the field-of-view (generated by the *vmifuscience* recipe) as zig-zagging patterns breaking the generally smooth look of the intensity distribution.

The optical-spectral distortions (coded in the extraction mask) are always recomputed from scratch by tracing the flat field spectra, and then by wavelength-calibrating the extracted arc lamp spectra. Contrary to what happens in the MOS data reduction task, the distortion models contained in the data headers are ignored.

The bad pixel table needs to be specified only if the cleaning of bad pixels is requested. In the calibration directories there is one CCD\_TABLE file for each quadrant, named *badpixel.q.tfits* (where *q* is the quadrant number increased by 4). Care should be taken in selecting the appropriate bad pixel tables for the spectral instrument modes (in the case of imaging data *q* is the quadrant number).

The line catalogues in the calibration directories are named *lcat\_grism.q.tfits* (where *grism* is the grism name, and *q* the quadrant number although there is no actual dependency from the quadrant number).

All the products of the *vmifucalib* recipe are shown in Table 7.19.2.

The extracted spectra are stored in the output images in a conventional order, with blue on the left and red on the right side. The images have 400 rows in the case of MR and HR observations, and 1600 rows in the case of LR observations. The spectra starting from the left side of each pseudo-slit are stored starting from the bottom rows of the output images. In the case of LR observations, the first 400 spectra from the pseudo-slit 1 are at the bottom, and the last 400 spectra from the pseudo-slit 4 are at the top.

Each image row corresponds to an IFU fiber position on the IFU head. This correspondence is described in a set of 8 tables located in the calibration directories (see Table 7.19.3). A subset of 4 tables refers to LR observations, with 1600 spectra per quadrant, and they are named *ifutableLRq.fits* (where *q* indicates the VIMOS

File name	DO category	Type	Explanation
ifu_master_screen_flat.fits	IFU_MASTER_SCREEN_FLAT	FITS	Combined flats
ifu_arc_spectrum_extracted.fits	IFU_ARC_SPECTRUM_EXTRACTED	FITS	Extracted arc spectra
ifu_flat_spectrum_extracted.fits	IFU_FLAT_SPECTRUM_EXTRACTED	FITS	Extracted flat spectra
ifu_trace.fits	IFU_TRACE	FITS	Extraction mask
ifu_ids.fits	IFU_IDS	FITS	Wavelength calibration
ifu_transmission.fits	IFU_TRANSMISSION	FITS	Transmission correction

Table 7.19.2: *Products of the vmifucalib recipe.*

Column name	Explanation
ROW	Image row, counted from the bottom starting from 1.
L	X coordinate on the IFU head, counted from left, ranging from 1 to 80.
M	Y coordinate on the IFU head, counted from bottom, ranging from 1 to 80.

Table 7.19.3: *IFU position table entries.*

quadrant number). A second subset of 4 tables should be used for MR and HR observations, with 400 spectra per quadrant, and they are named `ifutableHRq.fits`.

The content of the calibration tables generated by the recipe `vmifucalib` is described in Tables 7.19.4, 7.19.5, and 7.19.6.

Column name	Explanation
$C_i$	$i^{st}$ coefficient of the spectrum tracing polynomial.
RMS	Standard deviation of polynomial fit.

Table 7.19.4: *IFU extraction mask.*

In the extraction mask `ifu_trace.fits`, there are two table extensions for each active IFU pseudo-slit. Each table includes the coefficients of 400 polynomial fits, one for each fiber spectrum, starting from the first spectrum at the left end of a pseudo-slit. The first table extension of each pair is the actual extraction mask, obtained by polynomial fitting of the tracings on the whole spectral range. The second table extension is just a linear fitting of the tracing on a short range, used in the alignment of the extraction mask to the scientific spectra.

In the inverse dispersion solution `ifu_ids.fits` there is one table extensions for each active IFU pseudo-slit. Each table includes the coefficients of 400 polynomial fits, one for each fiber spectrum, starting from the first spectrum at the left end of a pseudo-slit.

The `ifu_transmission.fits` table includes the fiber-to-fiber relative transmission correction factors of 400 (in case of MR or HR observations) or 1600 (in case of LR observations) fiber spectra, starting from the first spectrum at the left end of the first pseudo-slit.

The `vmifucalib` parameters are listed in Table 7.19.7.

A more complete description of the used parameters meaning is given here:

Column name	Explanation
$C_i$	$i^{st}$ coefficient of the inverse dispersion polynomial.
RMS	Standard deviation of polynomial fit.
NLINES	Number of identified arc lamp lines used in fit.

Table 7.19.5: *Inverse dispersion solution.*

Column name	Explanation
TRANS	Relative transmission factor of fiber.

Table 7.19.6: *Relative transmission factors for all fibers.*

**AllowSingleFrames:** If this parameter is set, then a master flat field is produced also from a single input flat field exposure. In this case the *StackMethod* is ignored.

**ApplyTransmission:** If this parameter is set, then the computed fiber-to-fiber relative transmission correction factors are applied to all the extracted spectra.

**BiasMethod:** Method for bias removal from the input frames. The bias removal procedure is described in some detail in Section 9.3. Possible settings are:

**Master:** After master bias subtraction, prescan and overscan regions are trimmed away from the processed frame.

**Zmaster:** After master bias subtraction the overscan correction is applied before trimming away the overscan regions.

**CleanBadPixel:** Bad pixel correction on the master flat field. If this option is turned on, a bad pixel table should be specified in the input SOF (see Table 7.14.1, page 101). The bad pixel correction algorithm is described in Section 9.1, page 141.

**ComputeQC:** If this parameter is set, *Quality Control* (QC) parameters will be computed and written to the header of the output tables, and to three output QC PAF files named `qc0000.paf`, `qc0001.paf`, and `qc0001.paf`. These files are not classified as pipeline recipe products, as they are intermediate datasets that in the standard pipeline operations would be translated into new entries in the QC log file. Currently the QC parameters computed by *vmifucalib* are:

QC IFU LOST $i$ : Number of fibers that could not be traced on pseudo-slit  $i$ .

QC IFU TRACE $i$  RMS: Mean value of the RMS of the polynomial fitting obtained on each traced IFU spectrum on pseudo-slit  $i$ .

QC IFU IDS RMS: RMS of the IDS residuals, evaluated on the image of extracted arc lamp spectra.

QC IFU RESOLUTION $j$  LAMBDA: Wavelength of the arc lamp line chosen for determining the spectral resolution in the red ( $j = 1$ ), central ( $j = 2$ ), and blue ( $j = 3$ ) spectral regions.

QC IFU RESOLUTION $j$ : Spectral resolution in the red ( $j = 1$ ), central ( $j = 2$ ), and blue ( $j = 3$ ) spectral regions, averaged on all spectra, evaluated on an arc lamp spectrum line dependent on the

Parameter	Possible values	Explanation
AllowSingleFrames	true false	A single input flat is also allowed More than one input flat is required
StackMethod	Average Median MinMax Ksigma Auto	Master flat is average of input flats Master flat is median of input flats Master flat is obtained with min-max rejection Master flat is obtained with K-sigma clipping Optimal combination of input flats
KSigmaLow	<i>float</i> (sigma)	Low threshold for K-sigma clipping method
KSigmaHigh	<i>float</i> (sigma)	High threshold for K-sigma clipping method
MinRejection	<i>int</i>	No. of lowest rejected values for rejection method
MaxRejection	<i>int</i>	No. of highest rejected values for rejection method
BiasMethod	Master Zmaster	Bias removal with no overscan correction Bias removal with overscan correction
CleanBadPixel	true false	Clean bad pixels Do not clean bad pixels
ApplyTransmission	true false	Apply transmission correction to extracted spectra Do not apply transmission correction
MaxIdsRms	<i>float</i> (pixel)	Maximum tolerated RMS of residuals in IDS fit
LineIdent	FirstGuess Blind	Line identification based on first-guess models Line identification based on pattern recognition
MaxTraceRejection	<i>int</i>	Maximum percentage of rejected positions in tracing
ComputeQC	true false	Compute QC parameters Do not compute QC parameters

Table 7.19.7: *vmifucalib* parameters.

used grism. The spectral resolution is computed as the ratio between the arc lamp line wavelength, and its FWHM.

QC IFU RESOLUTION $j$  RMS: RMS of spectral resolution determined in the red ( $j = 1$ ), central ( $j = 2$ ), and blue ( $j = 3$ ) spectral regions.

QC IFU WAVECAL $j$  COEFF $i$ : Median  $i^{th}$  coefficient of the inverse dispersion solutions on pseudo-slit  $j$ , with  $i = 1, 2, \dots, n$  (where  $n$  is the degree of the polynomial used). In the case of MR and HR observations, this parameter is just computed for the active slit ( $j = 2$ ).

QC IFU TRACE $j$  COEFF $i$ : Median  $i^{th}$  coefficient of the fiber spectra tracing solutions on pseudo-slit 1, with  $i = 1, 2, \dots, n$  (where  $n$  is the degree of the polynomial used). In the case of MR and HR observations, this parameter is just computed for the active slit ( $j = 2$ ).

QC IFU REFROW $j$ : The reference row is the  $Y$  pixel position on the CCD where, for a given pseudo-slit  $j$ , each fiber spectrum is detected, identified, and conventionally begun to be traced. This parameter is reported here, because referenced by other IFU QC1 parameters.

QC IFU TRACE $j$  CENTRAL: On pseudo-slit  $j$ , this is the sequence number of the active fiber closest to the central CCD  $X$  pixel at the reference row (see QC IFU REFROW $i$ ).

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**QC IFU TRACE<sub>j</sub> SLOPE:** On pseudo-slit  $j$ , a linear fit is made to the tracing of the central spectrum (see **QC IFU TRACE<sub>i</sub> CENTRAL**), on a 400 pixels interval centered on the reference row (see **QC IFU REFROW<sub>i</sub>**). In absence of optical distortions, a perfect grism alignment would correspond to a zero slope.

**QC IFU FLUX LAMBDA<sub>i</sub>:** The flat field flux (see **QC IFU FLUX MEAN**) is measured on a wavelength interval starting ( $i = 1$ ) and ending ( $i = 2$ ) at the specified values.

**QC IFU FLAT FLUX:** The mean integrated signal, per fiber, per second, within the specified wavelength interval, is computed on all active pseudo-slits.

**KSigmaHigh:** Number of standard deviations above the median pixel value for rejecting a pixel value when *StackMethod* is set to “Ksigma”.

**KSigmaLow:** Number of standard deviations below the median pixel value for rejecting a pixel value when *StackMethod* is set to “Ksigma”.

**LineIdent:** Arc lines identification method. The identification procedure is described in some detail in Section 9.24.4. Possible settings are:

**Blind:** Arc lamp lines are identified without making use of first-guess IDS models. This method, based on pattern recognition, just requires the rough estimate of the expected spectral dispersion read from the input grism table.

**FirstGuess:** Arc lamp lines are identified on the basis of existing models of the spectral distortions, used as first-guesses.

**MaxIdsRms:** Maximum tolerated RMS of residuals in IDS fit (pixel). In the determination of the wavelength calibration, any polynomial fit not better than indicated, will be rejected.

**MaxRejection:** Number of highest pixel values to be rejected when *StackMethod* is set to “MinMax”.

**MinRejection:** Number of lowest pixel values to be rejected when *StackMethod* is set to “MinMax”.

**MaxTraceRejection:** Maximum percentage of rejected positions in fiber spectra tracing. In the fiber tracing operation, a number of pixel positions may be rejected because the detected position outlays the general trend, or because the signal level is too low. When the percentage of rejected positions is more than what is specified here, then the corresponding fiber is flagged as “dead” and excluded from further processing.

**StackMethod:** Combination method of input flat field exposures for master flat field creation. See Section 9.6 for a complete description of all the combination methods. Note that the master flat field is the frame where the fiber spectra tracing is performed, for the definition of the extraction mask. Possible settings of *StackMethod* are:

**Auto:** Given the number of input flat fields, an optimal frame combination method is selected. Currently this is always going to the method “Average”.

**Average:** The master flat field is the mean of the input frames.

**Ksigma:** The master flat field is the mean of the input frames, after K-sigma screening of pixel values. The number of sigma to be applied in the rejection is specified by the parameters *KSigmaLow* and *KSigmaHigh*.

**Median:** The master flat field is the median of the input frames.

**MinMax:** The master flat field is the mean of the input frames, after rejection of minimum and maximum values. The number of values to reject is specified by the parameters *MinRejection* and *MaxRejection*.

A description of the algorithms used in this recipe is given in Section 9.29, page 188.

## 7.20 vmifuscience

The VIMOS pipeline recipe *vmifuscience* is used to extract IFU scientific spectra applying the input extraction mask, after aligning it to the brightest spectra detected on the input exposure. The extracted spectra are then resampled at a constant wavelength step, after aligning the input wavelength calibration to the positions of a set of identified sky lines. The extracted spectra are eventually corrected for the relative differences in transmission from fiber to fiber, and they may optionally be flux calibrated.

The files to be included in the input SOF are listed in Table 7.20.1.

DO category	Type	Explanation	Required
IFU_SCIENCE	Raw frame	Scientific spectra	✓
MASTER_BIAS	Calibration	Master bias	✓
IFU_TRACE	Calibration	Extraction mask	✓
IFU_IDS	Calibration	Wavelength calibration	✓
IFU_TRANSMISSION	Calibration	Transmission correction	✓
EXTINCT_TABLE	Calibration	Atmospheric extinction table	
IFU_SPECPHOT_TABLE	Calibration	Spectro-photometric table	
CCD_TABLE	Calibration	Bad pixel table	

Table 7.20.1: *Input files for the vmifuscience recipe.*

The extraction mask, the wavelength calibration, and the relative transmission table, are those generated by the recipe *vmifucalib* (see Section 7.19, page 120).

A CCD table must be specified only if bad pixel cleaning is requested. In the calibration directories there is one CCD\_TABLE file for each quadrant, named *badpixel.q.tfits* (where *q* is the quadrant number increased by 4). Care should be taken in selecting the appropriate bad pixel tables for the spectral instrument modes (in the case of imaging data *q* is the quadrant number).

If a flux calibration is requested, a spectro-photometric table produced by the recipe *vmifustandard* must be specified together with an atmospheric extinction table (see Tables 7.18.2 on page 118, and 7.18.6 on page 120). Note that a flux calibration can be applied to the reduced data at a later stage, using the recipe *vmsspphot* (see Section 7.23, page 130).

All the products of the *vmifuscience* recipe are shown in Table 7.20.2.

The extracted spectra are stored in the output images in a conventional order, with blue on the left and red on the right side. The images have 400 rows in the case of MR and HR observations, and 1600 rows in the case of

File name	DO category	Type	Explanation
ifu_science_reduced.fits	IFU_SCIENCE_REDUCED	FITS	Reduced scientific spectra
ifu_science_reduced.fits	IFU_SCIENCE_FLUX_REDUCED	FITS	Flux calibrated spectra
ifu_fov.fits	IFU_FOV	FITS	Reconstructed field-of-view image

Table 7.20.2: *Products of the vmifuscience recipe.*

LR observations. The spectra starting from the left side of each pseudo-slit are stored starting from the bottom rows of the output images. In the case of LR observations, the first 400 spectra from the pseudo-slit 1 are at the bottom, and the last 400 spectra from the pseudo-slit 4 are at the top.

Each image row corresponds to an IFU fiber position on the IFU head. This correspondence is described in a set of 8 tables located in the calibration directories (see Table 7.19.3 on page 122, and its description in Section 7.19).

If a flux calibration is requested, then an IFU\_SCIENCE\_FLUX\_REDUCED image is also created. This image is identical to the IFU\_SCIENCE\_REDUCED one, but the spectra it contains are flux calibrated, and expressed in units of  $10^{-16}$  erg cm<sup>-2</sup> s<sup>-1</sup> Å<sup>-1</sup>. Note, however, that the obtained fluxes are valid only if the input IFU\_SPECPHOT\_TABLE is based on a standard star observed under similar atmospheric conditions.

The *vmifuscience* parameters are listed in Table 7.20.3.

Parameter	Possible values	Explanation
BiasMethod	Master Zmaster	Bias removal with no overscan correction Bias removal with overscan correction
CleanBadPixel	true false	Clean bad pixels Do not clean bad pixels
UseSkylines	true false	Use sky lines to align wavelength calibration Do not align wavelength calibration
UseSkyIndividual	true false	Align spectra to sky individually Same sky alignment for all spectra
CalibrateFlux	true false	Apply flux calibration to extracted spectra Do not apply flux calibration

Table 7.20.3: *vmifuscience parameters.*

A more complete description of the used parameters meaning is given here:

**BiasMethod:** Method for bias removal from the input frame. The bias removal procedure is described in some detail in Section 9.3. Possible settings are:

**Master:** After master bias subtraction, prescan and overscan regions are trimmed away from the processed frame.

**Zmaster:** After master bias subtraction the overscan correction is applied before trimming away the overscan regions.

**CalibrateFlux:** Flux calibration of the extracted spectra. If this option is turned on, an atmospheric extinction table and a spectro-photometric table (see tables 7.18.2 and 7.18.6, pages 118 and 120) should be specified in the input SOF. The flux calibration is applied as described in Section 9.10, page 147.

**CleanBadPixel:** Bad pixel correction on the scientific exposure. If this option is turned on, a bad pixel table should be specified in the input SOF (see Table 7.14.1, page 101). The bad pixel correction algorithm is described in Section 9.1, page 141.

**UseSkylines:** If this parameter is set, a number of sky lines are searched and identified in the input science exposure. Currently, just the four bright sky lines at 5577.338, 6300.304, 6363.780, and 8344.602 Ångstrom are used. The median offset from their expected positions along the dispersion direction is taken as a measure of the variation of the instrument flexure between the science exposure and the flat field and arc lamp exposures used for calibration. This offset is added to the constant term of the IDS polynomials (see Section 7.19, page 120), before using them in the spectral extraction task.

**UseSkyIndividual:** If this parameter is set, together with *UseSkylines*, the alignment of the wavelength solution to the observed positions of the reference sky lines is made independently for each fiber spectrum.

A description of the algorithms used in this recipe is given in Section 9.30, page 188.

## 7.21 vmifustandard

The VIMOS pipeline recipe *vmifustandard* is used to extract the IFU spectra of a spectro-photometric standard star applying the input extraction mask, after aligning it to the brightest spectra detected on the input exposure. The extracted spectra are then resampled at a constant wavelength step, after aligning the input wavelength calibration to the positions of a set of identified sky lines. The extracted spectra are corrected for the relative differences in transmission from fiber to fiber, they are sky subtracted, and added together to produce the total standard star spectrum. Finally, the instrument efficiency and the response curves are derived by comparison with the corresponding catalog spectrum.

The files to be included in the input SOF are listed in table 7.21.1.

DO category	Type	Explanation	Required
IFU_STANDARD	Raw frame	Scientific spectra	✓
MASTER_BIAS	Calibration	Master bias	✓
IFU_TRACE	Calibration	Extraction mask	✓
IFU_IDS	Calibration	Wavelength calibration	✓
IFU_TRANSMISSION	Calibration	Transmission correction	✓
EXTINCT_TABLE	Calibration	Atmospheric extinction table	✓
STD_FLUX_TABLE	Calibration	Spectro-photometric table	✓
CCD_TABLE	Calibration	Bad pixel table	

Table 7.21.1: *Input files for the vmifustandard recipe.*

The extraction mask, the wavelength calibration, and the relative transmission table, are those generated by the recipe *vmifucalib* (see Section 7.19, page 120).



An atmospheric extinction table and the standard star flux table must be specified (see Tables 7.18.2 and 7.18.3, page 118). A set of standard star flux tables, corresponding to the 30 spectro-photometric standard stars that are included in the VIMOS calibration plan ([8]), is available in the calibration directories. The names of these tables, and the name of the standard stars as reported in the FITS header keyword `ESO OBS TARG NAME`, are listed in Table 7.18.4, page 119. The table indicated in the SOF should match the content of the header entry `ESO OBS TARG NAME` of the input standard star exposure.

A CCD table must be specified only if bad pixel cleaning is requested. In the calibration directories there is one `CCD_TABLE` file for each quadrant, named `badpixel.q.tfits` (where  $q$  is the quadrant number increased by 4). Care should be taken in selecting the appropriate bad pixel tables for imaging and spectral instrument modes (in the case of imaging data  $q$  is the quadrant number).

All the products of the *vmifustandard* recipe are shown in Table 7.21.2.

File name	DO category	Type	Explanation
ifu_standard_reduced.fits	IFU_STANDARD_REDUCED	FITS	Reduced fiber spectra
ifu_fov.fits	IFU_FOV	FITS	Reconstructed field-of-view image
ifu_standard_extracted.fits	IFU_STANDARD_EXTRACTED	FITS	Total standard star spectrum
ifu_science_sky.fits	IFU_SCIENCE_SKY	FITS	Sky spectrum
ifu_specphot_table.fits	IFU_SPECPHOT_TABLE	FITS	Response curves

Table 7.21.2: *Products of the vmifustandard recipe.*

The extracted spectra are stored in the output images in a conventional order, with blue on the left and red on the right side. The images have 400 rows in the case of MR and HR observations, and 1600 rows in the case of LR observations. The spectra starting from the left side of each pseudo-slit are stored starting from the bottom rows of the output images. In the case of LR observations, the first 400 spectra from the pseudo-slit 1 are at the bottom, and the last 400 spectra from the pseudo-slit 4 are at the top.

Each image row corresponds to an IFU fiber position on the IFU head. This correspondence is described in a set of 8 tables located in the calibration directories (see Table 7.19.3 on page 122, and its description in Section 7.19).

The sky spectrum is determined as the median values of all the extracted spectra along the cross dispersion direction. The total spectrum is then computed as the sum of all the sky-subtracted spectra.

The output spectro-photometric table is derived in the same way as in the recipe *vmmosstandard*, and is described in that Section (see also Table 7.18.6, page 120).

The *vmifustandard* parameters are the same as for recipe *vmifuscience*, and they are listed in Table 7.20.3. The only exception is the parameter *CalibrateFlux*, missing in the *vmifustandard* recipe, and the parameter *ComputeQC*, that is typically set for monitoring the instrument efficiency at specific wavelengths.

A description of the algorithms used in this recipe is given in Section 9.31, page 189.

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## 7.22 **vmifucombine**

This recipe is used to compose the reconstructed images of the IFU field-of-view from different VIMOS quadrants into a single image. Such images are created by the recipes *vmifuscience* and *vmifustandard*. The input images must belong to different quadrants, so that there cannot be more than 4.

The mosaic is composed after a relative flux correction between the different input quadrants is applied.

## 7.23 **vmsspphot**

This recipe is used to apply a flux calibration to any number of 1D-extracted spectral frames generated by the recipes *vmmosobsstare*, *vmmosobsjitter*, *vmmoscombine*, and *vmifuscience*. The input set-of-frames will include a list of either `MOS_SCIENCE_REDUCED` or `IFU_SCIENCE_REDUCED` frames, all obtained from the same instrument quadrant and with the same instrument mode. An atmospheric extinction table `EXTINCT_TABLE`, and a spectro-photometric table consistent with the chosen instrument mode (that is either `MOS_SPECPHOT_TABLE` or `IFU_SPECPHOT_TABLE` ), shall also be added.

This recipe has just one configuration parameter, *ApplyResponse*, that may be set to `false` to indicate that just the atmospheric extinction correction should be applied to the input data. In that case an input spectro-photometric table is not required. If *ApplyResponse* is set to `true`, then the instrument response correction is also applied. The flux calibration is applied as described in Section 9.10, page 147.

A number of output calibrated frames, equal to the number of input spectral frames, will be created by this recipe. The products header keyword `ESO PRO AIRMASS` will always be set to zero, to indicate that an atmospheric extinction correction was applied. In case an instrument response curve is also applied, then the header keyword `EXPTIME` will be set to 1.0 seconds.

## 8 Geometrical distortions models

The reduction of VIMOS scientific data made by the VIMOS pipeline is based on a set of predefined models of the optical distortions affecting the instrument.

In the VIMOS pipeline, optical distortions modeling is obtained by simple polynomial fitting based on known quantities, such as celestial coordinates of astrometric stars, positions of pinholes on a calibration mask, or spectral lines wavelengths from a catalog, all compared to the positions of detected features and patterns on the CCD.

Pipeline recipes related to geometrical calibrations generate a set of IWS configuration files where the coefficients of the derived polynomials are stored. This information will be copied, when appropriate, from the IWS configuration files to the headers of any dataset generated by the VIMOS instrument.

Optical distortions are not expected to remain constant in time. Small changes are introduced by a changing orientation of the instrument within the gravitational field. A progressive aging of the structure, and possible interventions on the instrument, may also contribute to long term changes.

For this reason, the VIMOS pipeline recipes will use the distortion models contained in the datasets headers as “first guesses”, to be used as a starting point for further improvement of the solutions, adapting them to the momentary instrument distortions.

“First guesses” will work as long as they are close enough to the real distortions, ensuring a safe identification of the appropriate reference signals contained in the data. How much is “close enough” depends on a large number of factors, mainly related to the nature of the distortion, and to the robustness of the pattern matching algorithm of the involved pipeline recipe. This will be discussed in more detail in Section 9.

### 8.1 Polynomial models

The geometrical distortions introduced by the VIMOS + UT optics can be distinguished into *optical* and *spectral*, mirroring the fundamental instrument setups. Each optical and spectral distortion is in its turn described by a set of polynomial models. In some cases the polynomial models encode not just a distortion (intended as a transformation within the same coordinate system), but a transformation from a coordinate system to another which may include also the geometrical distortions.

Here is an overview of the polynomials used to model each distortion:

#### Optical

- Mask to CCD transformation (MAS2CCD)
  - Transformation matrix (scale, shift, rotation)
  - Two bivariate polynomial fits of the residuals (for the  $X$  and the  $Y$  CCD coordinates)
- CCD to Mask transformation (CCD2MAS)
  - Transformation matrix (scale, shift, rotation)
  - Two bivariate polynomial fits of the residuals (for the  $x$  and the  $y$  Mask coordinates)
- Sky to CCD distortion (SKY2CCD)

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- Bivariate polynomial fit of the residuals of CCD positions derived applying the WCS received from the TCS
- CCD to Sky distortion (CCD2SKY)
  - Inverse of the bivariate polynomial fit modeling the Sky to CCD distortion

During the data reduction process the Sky to CCD distortion model is converted by the pipeline into the CO matrix standard, used in the SAO WCSTools package [10].

## Spectral

- Zero Order Contamination (ZERO)
  - Two bivariate polynomials (separately for the  $X$  and the  $Y$  CCD coordinate) of mask coordinates *vs* CCD positions
- Optical Distortion (OPT)
  - Two bivariate polynomials (separately for the  $X$  and the  $Y$  CCD coordinate) of mask coordinates *vs* CCD positions
- Spatial Curvature (CRV)
  - *Local CRV*: Simple polynomial fits of local curvatures
  - *Global CRV*: Bivariate polynomial fits of the coefficients of local CRV *vs* CCD positions
- Inverse Dispersion Solution (IDS)
  - *Local IDS*: Simple polynomial fits of wavelengths *vs* CCD positions
  - *Global IDS*: Bivariate polynomial fits of the coefficients of local IDS *vs* CCD positions

The so-called “optical distortion model” is really a transformation from Mask to CCD coordinates valid for the spectral instrument setup, which includes the optical distortions at a conventional reference wavelength. The choice of a reference wavelength  $\lambda_o$  is in principle arbitrary, being just a conventional zero-point for all the spectral distortion models and transformations. In practice  $\lambda_o$  is chosen roughly in the middle of the valid spectral range of a given grism, possibly matching the wavelength of a bright and isolated line of the arc lamp catalog used for spectral calibrations.

The coefficients of all the polynomial fits are written to the appropriate VIMOS IWS configuration files, with the exception of the local CRV and IDS, whose coefficients are written instead into another pipeline product, the *extraction table* (see Section 7.14, page 103) in the case of MOS observations, and into the trace and IDS tables (see Section 7.19, pages 122 and 123) in the case of IFU observations.

Details on the algorithms applied by the relevant pipeline recipes can be found in Section 9. In the present section just a description of the geometrical distortion models is given.

## 8.2 Optical distortions

We include in this section any transformation between different coordinate systems while the instrument is configured in direct imaging mode.

Three fundamental coordinate systems can be considered:

- Celestial (Sky)
- Telescope focal plane (Mask)
- Instrument focal plane (CCD).

Only the transformations from CCD to Sky and from CCD to Mask (together with their inversions) are used and supported by the VIMOS pipeline.

### 8.2.1 CCD to Mask transformation and its inverse

The transformation from CCD to Mask coordinates is described by a two-layer model, consisting of a transformation including rotation, shift, and scaling, to which a bivariate polynomial fit of the residuals is added.

The base transformation can be expressed in the form

$$\begin{cases} x = a_{xx}X + a_{xy}Y + x_o \\ y = a_{yx}X + a_{yy}Y + y_o \end{cases}$$

where  $(X, Y)$  are CCD coordinates (pixels), and  $(x, y)$  the corresponding mask coordinates (millimetres).

If the mask were perfectly aligned with the CCD, only the diagonal elements of the matrix,  $a_{xx}$  and  $a_{yy}$ , would differ from zero, and they would correspond to the scale factor between mask and CCD (about 0.119 mm/pixel).

The coefficients of the base transformation for quadrant  $q$  are written to the entries of the `IMG_mask2ccd_q.cmf` IWS configuration file indicated in Table 8.2.1.

CCD to Mask linear transformation	
IMG_mask2ccd_q.cmf	coefficient
PRO CCD MASK X0	$x_o$
PRO CCD MASK XX	$a_{xx}$
PRO CCD MASK XY	$a_{xy}$
PRO CCD MASK Y0	$y_o$
PRO CCD MASK YY	$a_{yy}$
PRO CCD MASK YX	$a_{yx}$

Table 8.2.1: *CCD to Mask linear transformation coefficients.*

The residuals to the base transformation are modeled by a bivariate polynomial, that accounts for the higher order distortions of the instrument:

$$\begin{cases} \Delta x = \sum_{i,j} x_{ij} X^i Y^j & \text{with } 0 \leq i \leq m, 0 \leq j \leq m \\ \Delta y = \sum_{i,j} y_{ij} X^i Y^j & \text{with } 0 \leq i \leq m, 0 \leq j \leq m \end{cases}$$

The coefficients of the distortion for quadrant  $q$ , and the max degree of each variable of the bivariate polynomial, are written to the entries of the `IMG_mask2ccd_q.cmf` IWS configuration file indicated in Table 8.2.2.

CCD to Mask distortion model	
IMG_mask2ccd_q.cmf	coefficient
PRO CCD MASK XORD	$m$
PRO CCD MASK YORD	$m$
PRO CCD MASK X_ $i$ _ $j$	$x_{ij}$
PRO CCD MASK Y_ $i$ _ $j$	$y_{ij}$

Table 8.2.2: *CCD to Mask distortion model coefficients.*

Currently  $m$  must be kept equal to 3, for compatibility with the VMPS. The complete transformation from CCD to Mask is given by the sum of the base transformation with the distortion model.

The RMS (in millimetres) of the residuals of the complete transformation is also written to the IWS configuration file, at the entries `PRO CCD MASK XRMS` and `PRO CCD MASK YRMS`, together with the assigned temperature and time tag, written to `PRO CCD MASK TEMP` and `PRO CCD MASK DAYTIM`.

The inverse transformation, from Mask to CCD, is completely analogous to the CCD to Mask transformation.

### 8.2.2 CCD to Sky distortion and its inverse

For transforming CCD pixel coordinates to celestial coordinates and back, a WCS is written by the TCS to the FITS header of the observation data. This transformation is performed by the pipeline calling the appropriate functions of the SAO WCSTools package [10].

Once a WCS is established, the contribution of the optical distortions needs to be modeled. This is a distortion, meaning that the transformation is performed within the same coordinate system (in this case, the CCD). It is modeled by a two-branches bivariate polynomial analogous to the one used for the Mask to CCD transformations:

$$\begin{cases} X_v = \sum_{i,j} \alpha_{ij} X^i Y^j & \text{with } 0 \leq i \leq m, 0 \leq j \leq m \\ Y_v = \sum_{i,j} \beta_{ij} X^i Y^j & \text{with } 0 \leq i \leq m, 0 \leq j \leq m \end{cases}$$

We describe here for simplicity just the CCD to Sky model. This model is not converting image pixels into celestial coordinates (RA and Dec), but converts pixel positions  $(X, Y)$  on the CCD into virtual pixel positions  $(X_v, Y_v)$ , which are corrected for distortions and temperature effects. These virtual pixel positions can then be converted into celestial coordinates using the WCS information present in the data header (see Figure 8.2.1).

The coefficients of the distortion for quadrant  $q$ , and the max degree of each variable of the bivariate polynomial, are written to the entries of the `IMG_sky2ccd_q.cmf` IWS configuration file indicated in Table 8.2.3.

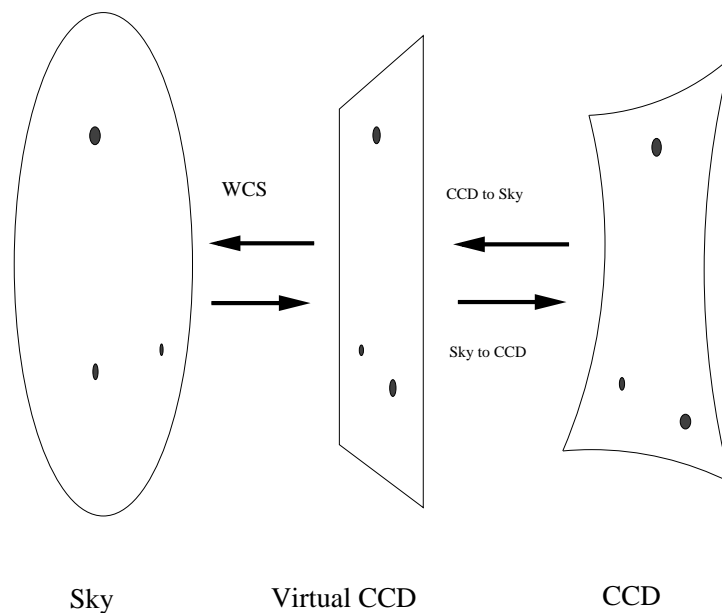


Figure 8.2.1: *Transformations and distortions between sky and CCD.*

CCD to Sky distortion model	
IMG_sky2ccd_q.cmf	coefficient
PRO CCD SKY XORD	$m$
PRO CCD SKY YORD	$m$
PRO CCD SKY X <sub><math>i</math></sub> <sub><math>j</math></sub>	$\alpha_{ij}$
PRO CCD SKY Y <sub><math>i</math></sub> <sub><math>j</math></sub>	$\beta_{ij}$

Table 8.2.3: *CCD to Sky distortion model coefficients.*

For  $m$  a value of 3 is currently chosen.

The RMS of the residuals of the models are also written to the IWS configuration file, at the entries PRO CCD SKY XRMS and PRO CCD SKY YRMS, together with the assigned temperature and time tag, written to PRO CCD SKY TEMP and PRO CCD SKY DAYTIM.

The inverse model would simply produce the  $(X, Y)$  coordinates of the real CCD from the  $(X_v, Y_v)$  virtual coordinates obtained by applying the WCS to (RA, Dec) positions.

The pipeline converts these distortion models into the CO-matrix convention that is then written to the FITS headers of the reduced science images.

### 8.3 Spectral distortions

We include in this section any transformation between different coordinate systems while the instrument is configured in spectral (MOS or IFU) mode.

Four fundamental coordinate systems can be considered:

- Celestial (Sky)
- Telescope focal plane (Mask)
- Instrument focal plane (CCD).
- Spectral wavelength (Ångstrom).

Only the transformations from Mask to CCD and from CCD to wavelength are currently used and supported by the VIMOS pipeline.

### 8.3.1 Zero order contamination model

*Currently not implemented*

### 8.3.2 Optical distortion model

The optical distortion model of the grism is really a direct transformation from  $(x, y)$  mask coordinates to  $(X, Y)$  CCD coordinates, valid for a conventional reference wavelength  $\lambda_o$ .

The model can be expressed in the form

$$\begin{cases} X = \sum_{i,j} a_{ij} x^i y^j & \text{with } 0 \leq i \leq m, 0 \leq j \leq m \\ Y = \sum_{i,j} b_{ij} x^i y^j & \text{with } 0 \leq i \leq m, 0 \leq j \leq m \end{cases}$$

where  $(X, Y)$  are CCD coordinates (pixels), and  $(x, y)$  the corresponding mask coordinates (millimetres).

The coefficients of the distortion for quadrant  $q$ , and the max degree of each variable of the bivariate polynomial, are written to the entries of the `MOS_wavecal_grism_name_q.cmf` IWS configuration file indicated in Table 8.3.1.

Optical distortion model	
MOS_wavecal_grism_name_q.cmf	coefficient
PRO OPT DIS XORD	$m$
PRO OPT DIS YORD	$m$
PRO OPT DIS X_ $i$ _ $j$	$a_{ij}$
PRO OPT DIS Y_ $i$ _ $j$	$b_{ij}$

Table 8.3.1: *Optical distortion model coefficients.*

For  $m$  a value of 3 is currently chosen.



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The RMS of the residuals of the model is also written to the IWS configuration file, at the entries `PRO OPT DIS XRMS` and `PRO OPT DIS YRMS`, together with the assigned temperature and time tag, written to `PRO OPT DIS TEMP` and `PRO OPT DIS DAYTIM`.

This model provides the reference on which both the spatial curvature and the inverse dispersion models are based.

In the specific case of IFU data reduction, a global optical distortion model is not really computed, and a zeropoint for all other distortion models is defined independently for each fiber.

### 8.3.3 Spatial curvature model

The spectrum corresponding to the position  $(x, y)$  on the mask traces a curve on the CCD. The spatial curvature model is used to determine this curve as a function of the mask coordinates.

The modeled quantity is the deviation  $\Delta X$  as a function of the distance  $\Delta Y$  from the  $(X, Y)$  CCD coordinates obtained applying the optical distortion model to the given  $(x, y)$  mask coordinate (see Section 8.3.2 and Figure 8.3.1).

This is the *local* curvature model, that can be expressed in the form

$$\Delta X = \sum_i c_i \Delta Y^i$$

with  $0 \leq i \leq m$  (with  $m$  currently set to 2).

The coefficients of the local curvature models, defined for each detected spectral edge on a flat field exposure, are written to the *extraction table* (see Section 7.14). It should be noted that the coefficient  $c_o$  is always equal to zero (for any  $(x, y)$ ), as it is implied by the curvature model definition.

The coefficients  $c_i$  depend on the  $(x, y)$  mask coordinates, and can be modeled by the  $m$  bivariate polynomials:

$$c_i = \sum_{j,k} \Gamma_{i,jk} x^j y^k$$

with  $0 \leq j \leq n$  and  $0 \leq k \leq n$  (with  $n$  currently set to 2).

The set of polynomials modeling the coefficients of the local curvature models is known as the *global* curvature model. All the coefficients for quadrant  $q$  and grism *grism\_name*, with the max degree for each variable of all the simple and the bivariate polynomials, are written to the entries of the `MOS_wavcal_grism_name_q.cmf` IWS configuration file indicated in Table 8.3.2.

Since all the  $c_i$  are zero for  $i = 0$ , it immediately follows that all the  $\Gamma_{o,jk}$  (*i.e.*, all the `PRO CRV MOD_0_j_k`) are also zero. They are written nevertheless to the data headers for consistency in the description of the polynomial models produced by the VIMOS pipeline recipes.

The temperature and the time tag assigned to the curvature model are identical to the ones of the inverse dispersion solution (see next section). The CRV and the IDS models are always derived from flat field and arc lamp exposures obtained (almost) simultaneously, to ensure that they are compatible with each other.

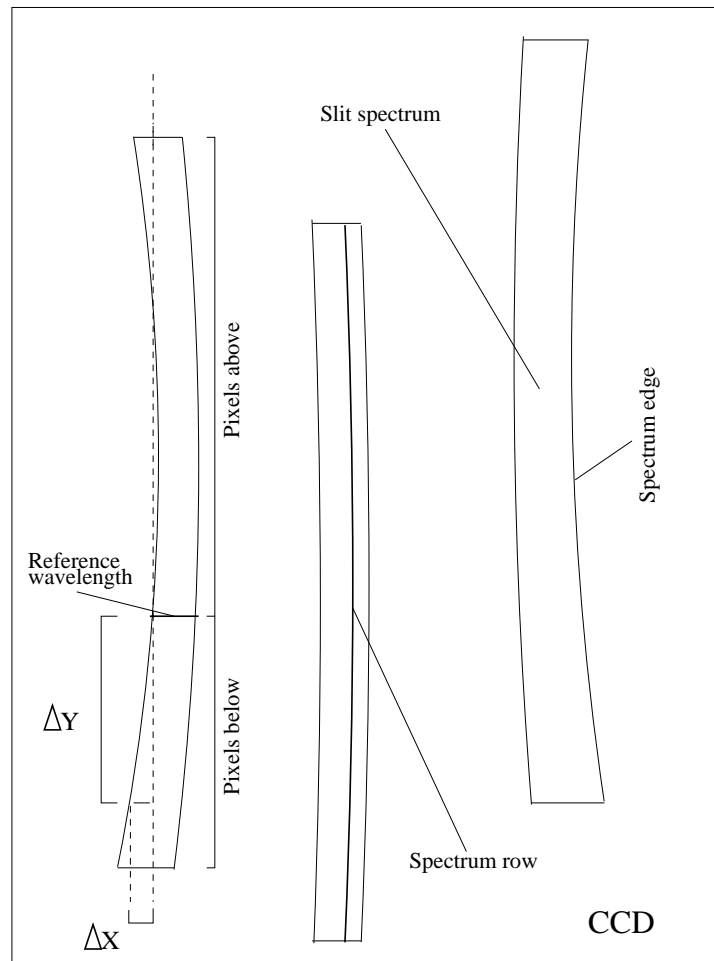


Figure 8.3.1: *MOS slit spectra on a CCD.*

In the specific case of IFU data reduction, a global curvature model is not really computed. The local curvatures are modeled independently for each fiber by a direct polynomial fit of absolute  $X$  vs  $Y$  CCD coordinates obtained from the fiber tracing task.

### 8.3.4 Inverse dispersion solution

As seen in Section 8.3.2, the optical distortion model is used to determine the position  $(X, Y)$  on the CCD corresponding to a position  $(x, y)$  on the mask, valid for a conventional reference wavelength  $\lambda_o$ .

In VIMOS the light is dispersed by the grism along the  $Y$  CCD coordinate, and therefore the wavelength calibration consists of a relation between the wavelength and the  $\Delta Y$  distance from the  $Y$  position obtained applying the optical distortion model to  $(x, y)$ .

The modeled quantity is the deviation  $\Delta Y$  as a function of the wavelength difference  $\Delta\lambda = \lambda - \lambda_o$ , expressed as usual with a polynomial fit that represents the *local* inverse dispersion solution (IDS):

Global curvature model	
MOS_wavecal_grism_name_q.cmf	coefficient
PRO CRV POL ORD	$m$
PRO CRV MOD XORD	$n$
PRO CRV MOD YORD	$n$
PRO CRV MOD_i_j_k	$\Gamma_{i,jk}$

Table 8.3.2: *Global curvature model coefficients.*

$$\Delta Y = \sum_i d_i \Delta \lambda^i$$

with  $0 \leq i \leq m$  (with  $m$  currently set to 3 for LR grisms, and to 4 for MR and HR grisms, being the lowest possible polynomial degree at which the residuals of the fit display a random distribution). The coefficients of the local IDS models, defined for each point corresponding to a different  $X$  CCD pixel for each slit of the mask, are written to the *extraction table* (see Section 7.14, page 103).

The coefficients  $d_i$  depend on the  $(x, y)$  mask coordinates, and can be modeled by the  $m + 1$  bivariate polynomials:

$$d_i = \sum_{j,k} \Lambda_{i,jk} x^j y^k$$

with  $0 \leq j \leq n$  and  $0 \leq k \leq n$  (with  $n$  currently set to 3).

The set of polynomials modeling the coefficients of the local IDS models is known as the *global IDS*. All the coefficients for quadrant  $q$  and grism *grism\_name*, with the max degree for each variable of all the simple and the bivariate polynomials, are written to the entries of the MOS\_wavecal\_grism\_name\_q.cmf IWS configuration file indicated in Table 8.3.3.

Global inverse dispersion solution	
MOS_wavecal_grism_name_q.cmf	coefficient
PRO IDS REL ORD	$m$
PRO IDS MAT XORD	$n$
PRO IDS MAT YORD	$n$
PRO IDS MAT_i_j_k	$\Lambda_{i,jk}$

Table 8.3.3: *Global inverse dispersion solution coefficients.*

The RMS of the residuals of the model is also written to the IWS configuration file, at the entry PRO IDS MAT YRMS (the entry PRO IDS MAT XRMS is unused, for obvious reasons). The temperature and time tag assigned to the model are written to PRO IDS MAT TEMP and PRO IDS MAT DAYTIM.

In the specific case of IFU data reduction, a global inverse dispersion solution is not really computed. Just the local wavelength calibration described above is computed separately for each fiber.

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### 8.3.5 Slit spectra extraction

Probably the best way to summarise the complete modeling of spectral distortions is to see it applied to the problem of extracting a slit spectrum from a raw image.

This is equivalent to finding what CCD coordinates correspond to a given position on the mask and to a given wavelength.

Let's indicate the spectral distortion models defined in the previous sections using the symbols  $OPT$ ,  $CRV$ , and  $IDS$ . Then the  $(X, Y)$  CCD coordinate corresponding to  $(x, y, \lambda)$  are given by:

$$\begin{cases} X = OPT_x(x, y) + CRV(IDS(\lambda)) \\ Y = OPT_y(x, y) + IDS(\lambda) \end{cases}$$

This results in a wavelength calibrated slit spectrum, corrected for the spectral and the spatial distortions.

## 9 Algorithms

In this section the data reduction procedures applied by the 23 pipeline recipes currently in use (see Section 5.1) are described in some detail. Common algorithms, as cosmic rays removal or bad pixel cleaning, are described separately.

### 9.1 Bad pixel cleaning

Bad pixel cleaning consists of replacing any bad pixel value with an estimate based on a set of surrounding *good* pixel values. This operation is generally applied to science product frames, having little or no sense when applied to master calibration products. Nevertheless all the VIMOS pipeline recipes allow bad pixel cleaning on any product frame, for debug reasons or for any other purpose that may be appropriate.

The routine currently used by the VIMOS pipeline recipes performs a bad pixel correction based on the content of a given bad pixel table (CCD\_TABLE). If the number of bad pixels is more than 15% of the total number of CCD pixels, the correction is not applied.

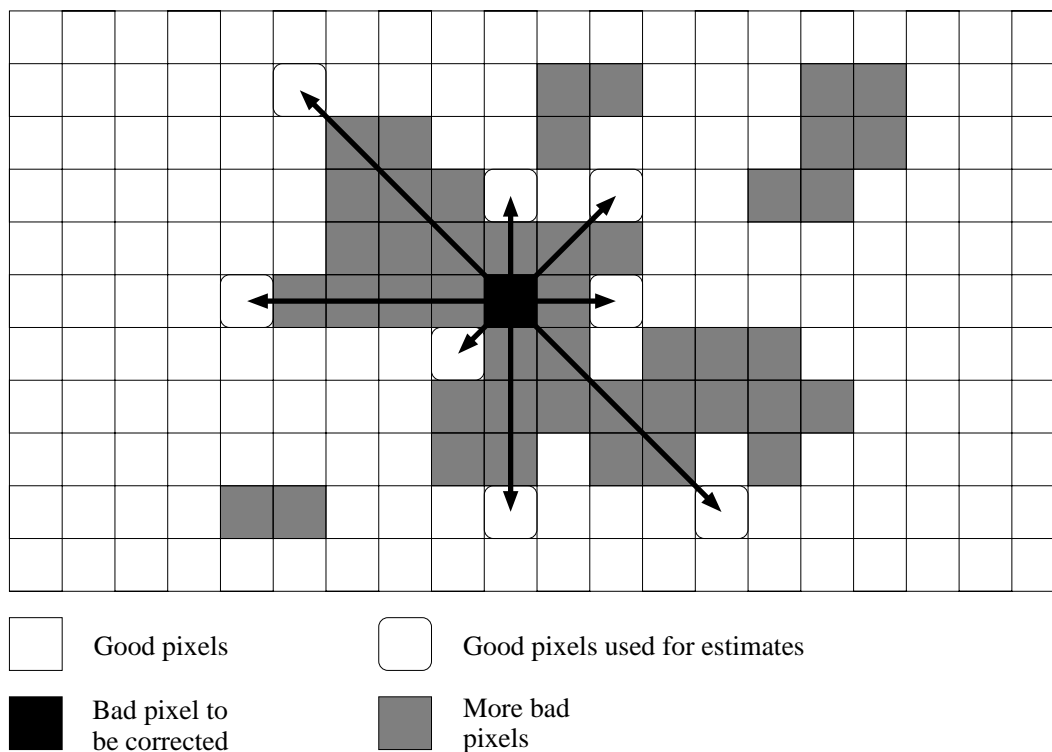


Figure 9.1.1: *Good pixels to be used in the estimate of a given bad pixel are searched along the indicated directions.*

Any bad pixel is given a new value, computed as follow: the closest good pixels along the vertical, the horizontal, and the two diagonal directions are found (see Figure 9.1.1). This search is done within a distance of 100 pixels.

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If no good pixel is found within this range, then the bad pixel is not corrected. All the good pixels found within range will be used to compute the bad pixel value.

For each of the four fundamental directions, an estimate of the considered bad pixel can generally be obtained. If two good pixel values are available for a given direction, the estimate is their linear interpolation at the bad pixel position. If just one good pixel value is available for a given direction, then the value itself will be the estimate of the bad pixel value. No estimate can be obtained from directions where no good pixel was found.

If the available number of estimates is greater than 1, the bad pixel value is taken as the median of the estimates (defining the median of an even number of values as the mean of the two central values), otherwise it is simply set to the single estimate available.

## 9.2 Cosmic rays removal

The core of a cosmic rays removal procedure is to determine what is and what is *not* a cosmic ray. The algorithm used for this purpose by the VIMOS pipeline recipes is the same applied by the MIDAS command `FILTER/COSMIC`, with some extensions.

Initially all pixels having an abnormal excess with respect to the local noise level are flagged as possibly belonging to a cosmic ray event (that typically would involve a group of contiguous pixels). A candidate is selected at any pixel  $(x, y)$  having a value  $F(x, y)$  exceeding a given threshold. This threshold, expressed in units of noise sigma, is specified by the recipe parameter *CosmicsThreshold*. A value 4.0 gives typically good results. The theoretical noise  $N(x, y)$  of the image at any given pixel position  $(x, y)$  is estimated in ADU as

$$N(x, y) = \sqrt{r^2 + \frac{M(x, y)}{g}}$$

where  $M(x, y)$  is the median value of the 8 pixels surrounding the  $(x, y)$  position and  $r$  is the read-out-noise, both in ADU, and  $g$  is the gain factor in  $e^-/ADU$ . Then a pixel  $(x, y)$  is taken as a cosmic ray candidate if

$$F(x, y) > k \cdot N(x, y)$$

with  $k$  the number of noise sigmas used in thresholding.

After this step is completed, all the groups of contiguous cosmic rays candidates are identified. For each group, the position of its maximum pixel value is determined, and the mean  $\overline{F}_8$  of its 8 surrounding pixels is computed. A given group will be taken as a cosmic ray event if it fulfils the condition

$$F_{max} - S > R \cdot (\overline{F}_8 - S)$$

where  $F_{max}$  is the maximum pixel value within the considered group,  $S$  the fundamental background level (corresponding to the sky level in imaging science exposures), and  $R$  is a shape parameter for discriminating between objects and cosmic rays. The ratio  $R$  is specified by the recipe parameter *CosmicsRatio*. A value of 2.0 gives typically good results.

Once all the pixels affected by cosmic ray events has been located and listed in a cosmic ray events table, their values are interpolated using the procedure described in Section 9.1. If a bad pixel table is also given to a recipe, then the bad pixels are avoided in the interpolation procedure.

### 9.3 Bias subtraction

Removing the bias from any raw frame is a relatively simple process, but not simple enough to avoid a description on its own.

A master bias frame (MASTER\_BIAS) is used to remove the bias level (and, if present, the fixed-pattern-noise related to the bias) from a raw frame. Typically a master calibration is produced with its overscan regions trimmed, and if this is the case with the master bias used then its missing overscan regions are extrapolated by repeating the signal contained in its border regions with equal size.

The master bias is subtracted from the raw data frame, whose overscan regions are then trimmed away. Optionally (when the *BiasMethod* recipe parameter is set to “Zmaster”) the residual signal in the overscan regions is averaged along the *X* CCD coordinate, and the obtained mean *Y* values are modeled with a second order polynomial fitting. This model is then subtracted from the rest of the image.

### 9.4 Dark subtraction

Subtracting the dark current component from any raw frame consists of multiplying an input master dark frame by the exposure time (in seconds) of the frame to be corrected, and then subtract such rescaled dark frame from it. The dark level is quite low for VIMOS CCDs (about  $5 \text{ e}^- \cdot \text{h}^{-1} \cdot \text{pixel}^{-1}$ ), so this operation would be in most cases superfluous.

### 9.5 Flat field correction

The flat field correction merely consists of dividing the frame to be corrected by a given master sky flat field frame produced by the recipe *vmimflatsky* for direct imaging observation (see Section 9.15, page 151), or produced by the recipe *vmisflat* for MOS observations (see Section 9.23, page 157).

### 9.6 Frame combination

A common task to many of the VIMOS pipeline recipes is the combination of several frames of the same kind. Currently four basic frame combination methods are available:

Average of frames:

Each combined frame pixel is the average of all the corresponding pixel values in the input frames. In this case at least two input frames are required.

Median of frames:

Each combined frame pixel is the median of all the corresponding pixel values in the input frames. In this case at least three input frames are required. In case of an even number of input frames, the median value is taken as the mean of the two central values.

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Rejection of minimum-maximum values:

Each combined frame pixel is the average of all the corresponding pixel values in the input frames, after rejecting a given number of minimum and maximum values from the set. In this case the number of input frames should be greater than the number of rejected values.

K-sigma rejection:

The median value of each pixel of the input frames is computed, and the standard deviation of all the pixel values from the median is evaluated. Each combined frame pixel is the average of all the corresponding pixel values in the input frames, after rejecting any pixel value deviating more than a given number of standard deviations. In this case, at least four input frames are required.

Combination methods different from averaging should, in principle, only be applied to the special case of statistically homogeneous set of frames. However, as a preventive measure taken in the VIMOS pipeline recipes, before applying those combination methods the input images are rescaled to a common level, chosen as the median level of the first input frame to which all the other frames median levels are aligned. This is still not a statistically valid way to proceed, since the noise level of each image is different, and methods like the K-sigma rejection would lose any real meaning.

## 9.7 Blind arc lamp lines identification

Starting with the VIMOS pipeline release 2.0, a new method for arc lamp line identification is applicable. This method may turn useful in the reduction of data for which the available first-guess distortion models turn out to be too inaccurate (perhaps due to mechanical instabilities of the instrument), or even missing (as it would be the case, for instance, with data obtained with a new grism).

In order to work, this method just requires a rough expectation value of the spectral dispersion (in Å / pixel), and a line catalog. The line catalog should include *just* lines that are expected somewhere in the CCD exposure of the calibration lamp.<sup>14</sup>

From the arc lamp spectra extracted following the available spatial curvature model, arc lamp lines candidates are selected and their positions on the CCD are determined. Typically, the arc lamp lines candidates will include light contaminations, cosmic rays hits, and other unwanted signal, but only in very extreme cases this will prevent the pattern recognition algorithm to identify all the spectral lines.

Currently any portion of the arc lamp spectrum peaking above a given threshold (measured relatively to the local background level) is selected as an arc lamp line candidate. In general the default threshold applied by the pipeline works well, but in some cases it may be helpful to lower it, in order to catch more (faint) lines, or to raise it, in order to avoid a too noisy background or a large number of fainter contaminations (coming perhaps from the second order dispersion of a multiplexed spectrum). Care should be taken in avoiding too low thresholds, that would pick up too much noise from the background, or too high thresholds, that would miss one or more valid arc lamp lines, leaving the pattern recognition algorithm without a pattern to match.<sup>15</sup>

<sup>14</sup>The line catalog represents the pattern that should be searched on the CCD, and adding extra lines would destroy this pattern. Note, however, that a catalog including extra lines at its blue and/or red ends would still be acceptable.

<sup>15</sup>A safer algorithm for the selection of arc lamp candidates is going to be made available in the next pipeline release.



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As a general rule, it is important to ensure that (almost) all the line catalog entries have their counterpart on the CCD.<sup>16</sup> In practice, it is safe to have more candidates on the CCD than lines in the input line catalog: the pattern recognition would succeed even in the case the spectra on the CCD contained more arc lamp lines than actually listed in the input line catalog.

## 9.8 Sky fringing correction

From a jittered observation, both in imaging and in MOS mode, a map of the sky can be obtained by median-stacking the input exposures (see Section 9.6, page 143). This sky map can then be subtracted from each input exposure before any further processing. Naturally, if a fringing pattern is present it will as well be eliminated from the data.

This method is not always applicable: if the observed field is too crowded and/or the jittering step is smaller than the extension of any of the observed objects, unwanted “ghosts” would appear on the sky map. It is important to carefully examine the sky map produced by the data reduction recipe, before trusting the results of the fringing correction.

It should also be noted that subtracting a sky map created by median-stacking the input exposures will increase the random noise on the reduced data. In order to minimise this effect, it is advisable to apply the fringing correction only if a large number (say, at least 5) of jittered exposures obtained at *different* offsets is available. That would also help to reduce the probability of “ghosts” on the generated sky map.

Another problem with this method is coming from the sky brightness changing during the observation. This is particularly important in the case of MOS observations, where the exposure times are typically much longer than in imaging, and the different components of the sky spectrum (continuum and emission lines systems) may display different variability patterns.

Nothing is done yet to keep into account a possible sky variability in the case of imaging observations. In the case of MOS observations, instead, systematic residuals are eliminated following different strategies, depending on the fringing correction method applied:

**Raw method:** A sky + fringes map is created from the median stacking of all the bias subtracted input frames. If the sky changed between exposures, the subtraction of the median sky will leave in general some systematic residuals on each data frame. Such residuals are removed at a later step by the sky modeling task, that blindly will treat them as “sky”.

**Resampled method:** This method differs from the *Raw* method only with respect to the point at which the median stacking of frames is applied. In this case the median map is created after the slit spectra are resampled at a constant wavelength step and the sky is removed by the standard sky modeling task. This map is then subtracted from each processed frame.

The median map obtained by the *Resampled* method should generally be regarded as a residuals map, rather than a fringes map. In fact, the sky modeling task is applied in this case to a sky that still includes its own fringes: if a median sky level is computed at each wavelength, its value would depend on the changing position

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<sup>16</sup>Losses on the red and/or blue ends are unimportant, however, because even parts of the pattern can be safely identified.

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of the object along its slit, while if the sky level is computed by polynomial interpolation, the polynomial would tend to fit both sky and fringes.

The choice of what method to apply is not simple. Clearly, if the sky displays no variability during the observation the *Raw* method is the theoretically correct one, and should be preferred: not only because the object detection task is more efficient if applied to spectra where sky fringes have already been removed, but also because with the *Resampled* method an apparent sky variability may be introduced, even when the sky is perfectly constant.<sup>17</sup>

On the other side, if the sky spectrum is strongly changing between exposures, the *Resampled* method tends to give the best results, as the above mentioned drawbacks are outweighed by the advantage of evaluating and removing the changing sky on a frame-by-frame basis.

Probably the only safe way to proceed is to reduce the data applying both methods, and judge *a posteriori* the quality of the sky fringing removal on the extracted object spectra.

## 9.9 Computation of the spectral efficiency

The efficiency of an instrument is defined as the ratio between detected photons and incoming photons, and can be derived by comparing the observed fluxes with the tabulated fluxes of known objects.

The spectral efficiency of the VIMOS instrument is obtained in the following way:

The extracted standard star spectrum,  $X(\lambda)$  is converted into  $e^- s^{-1} \text{ \AA}^{-1}$ :

$$S(\lambda) = \frac{g X(\lambda)}{t \Delta\lambda}$$

where  $g$  is the gain factor in  $e^- / \text{ADU}$ ,  $t$  the exposure time in seconds, and  $\Delta\lambda$  the constant wavelength step at which the spectrum was resampled after its calibration in wavelength.

The magnitude losses  $\Delta m(\lambda)$  listed in the column EXTINCTION of the atmospheric extinction table (see Table 7.18.2, page 118) are turned into flux losses, and applied to the observed spectrum:

$$S_o(\lambda) = S(\lambda) 10^{0.4 a \Delta m(\lambda)}$$

where  $S_o(\lambda)$  is the spectrum at airmass zero and  $a$  is the airmass of the standard star observation. The values of the atmospheric extinction are linearly interpolated from the tabulated values for all the wavelength of the observed spectrum. At those wavelengths where no atmospheric extinction data are available,  $S_o(\lambda)$  is set to zero.

The standard star catalog fluxes  $C(\lambda)$ , given in  $\text{erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ , are converted into photons collected by the telescope using

$$F(\lambda) = C(\lambda) \frac{A_t}{h\nu}$$

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<sup>17</sup>Since in different exposures the object has different positions along the slit, then the sky evaluation will be biased by different parts of the fringing profile.

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Considering  $A_t = 5.18 \cdot 10^5 \text{ cm}^2$  the VLT efficient area, and  $hc = 1.98 \cdot 10^{-8} \text{ erg } \text{\AA}$ , one derives

$$F(\lambda) = 2.6 \cdot 10^{-3} C(\lambda) \lambda$$

The efficiency is finally computed as

$$E(\lambda) = \frac{S_o(\lambda)}{F(\lambda)}$$

The efficiency  $E(\lambda)$  is set to zero at those wavelengths where no standard star catalog fluxes are available, and is written to the column `RAW_EFFICIENCY` of the output spectro-photometric table (see Table 7.18.6, page 120).

The response curve used in the flux calibration of observed scientific spectra (see next Section) is obtained by:

$$R(\lambda) = \frac{C(\lambda)}{S_o(\lambda)}$$

$R(\lambda)$  is set to zero where no standard star catalog fluxes are available, and is written to the column `RAW_RESPONSE` of the output spectro-photometric table.

As a final step, both  $E(\lambda)$  and  $R(\lambda)$  are passed with a very broad median filter and finally fit by a high degree polynomial, in order to derive a heavily smoothed version of the curves.<sup>18</sup> The smoothed curves are written as well to the output spectro-photometric table, at the columns `EFFICIENCY` and `RESPONSE`.

## 9.10 Flux calibration

Scientific spectra extracted by the recipes *vmmosobsstare*, *vmmosobsjitter*, and *vmifuscience*, can be calibrated in flux by specifying an atmospheric extinction table (see Table 7.18.2, page 118), and an appropriate spectro-photometric table (see Table 7.18.6, page 120). The spectro-photometric table is the primary product of the recipes *vmmosstandard* and *vmifustandard*, and it must be derived from a standard star observation made with the same grism, the same filter, the same VIMOS quadrant, and the same instrument mode (IFU or MOS).

An extracted scientific spectrum,  $X(\lambda)$ , is flux calibrated in the following way:

The spectrum is first converted into  $e^- \text{ s}^{-1} \text{ \AA}^{-1}$ :

$$S(\lambda) = \frac{g X(\lambda)}{t \Delta\lambda}$$

where  $g$  is the gain factor in  $e^- / \text{ADU}$ ,  $t$  the exposure time in seconds, and  $\Delta\lambda$  the constant wavelength step at which the spectrum was resampled after its calibration in wavelength.

The magnitude losses  $\Delta m(\lambda)$  listed in the column `EXTINCTION` of the atmospheric extinction table are turned into flux losses, and applied to the observed spectrum:

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<sup>18</sup>The preliminary median filtering has mainly the purpose to eliminate obvious atmospheric (local) absorption bands, and to give all weight to the spectral continuum of the observed standard star.

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$$S_o(\lambda) = S(\lambda) 10^{0.4 a \Delta m(\lambda)}$$

where  $S_o(\lambda)$  is the scientific spectrum at airmass zero and  $a$  is the airmass of the scientific observation. The values of the atmospheric extinction are linearly interpolated from the tabulated values for all the wavelength of the observed spectrum. At those wavelengths where no atmospheric extinction data are available,  $S_o(\lambda)$  is set to zero.

Finally, the flux calibrated spectrum is derived as

$$C(\lambda) = S_o(\lambda) R(\lambda)$$

where  $R(\lambda)$  is the content of the `RESPONSE` column in the specified spectro-photometric table (see section 9.9, page 146).

The accuracy of the flux calibration mainly depends on the instrument efficiency and other external factors (as the timing of the shutters, the slit width, the seeing conditions and the airmass during both the scientific and the standard star observations). However, excluding sources of systematic error, the applied method reaches an accuracy of better than 0.5% at spectral efficiencies greater than 10%.

## 9.11 vmdet

This recipe carries out the following fundamental steps:

1. Determining the read-out-noise.
2. Bias subtraction from all input flat fields.
3. Creating photon transfer curve, determining the gain factor.
4. Bad pixels identification.

A description of each step is given in the following sections.

### 9.11.1 Read-out-noise determination

Before subtracting the bias from the input flat field frames, the *read-out-noise* (RON) is evaluated from the flat fields overscan regions. Each overscan region is subtracted from itself shifted by 1x1 pixels, and the variance  $V$  of the difference image is determined. The RON is estimated as:

$$r = \sqrt{\frac{V}{2}}$$

The mean value of the RON values obtained from each overscan region is the estimated RON of the CCD (in ADU). At a later step, after the determination of the gain factor, the RON will be converted into electrons and written to the output bad pixel table header keyword `ESO DET OUT1 RON`.

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### 9.11.2 Bias subtraction

The master bias is subtracted from each of the flat field using the “*Zmaster*” method, described in detail in Section 9.3.

### 9.11.3 Photon transfer curve and gain factor determination

The gain determination is based on the paper by L. Mortara and A. Fowler [12]. The photon transfer curve is the relation between the observed signal level and the observed variance of this signal. In principle, both RON and gain can be obtained by least squaring the relation

$$V = \left(\frac{r}{g}\right)^2 + \frac{S}{g}$$

where  $V$  is the variance of the bias subtracted signal  $S$  (in ADU),  $g$  is the unknown gain factor in  $e^-/\text{ADU}$  (corresponding to the data header keyword `ESO DET OUT1 CONAD`), and  $r$  is the read-out-noise in  $e^-$ .

Since the relation between the signal and its variance is linear, we can build the photon transfer curve from the average signal and variance determined on just a portion of the chip.

From the central 200 x 200 pixel region of the CCD four different photon transfer curves are derived, one from each quarter of this region. This is a way to obtain independent determinations of the gain factor, and allow an estimate of the statistical error on the final result.

For each pair of flat fields with equal exposure time the median value of the signal within the selected regions is computed, while the variance is evaluated from the difference of the pair of frames.

The final gain factor is determined as the mean

$$g = \frac{\sum_i g_i}{4}$$

where  $g_i$  are the gain values obtained from the linear fitting of the four independent photon transfer curves. The error on the gain is estimated as

$$\Delta g = \frac{1}{2} \sqrt{\frac{\sum_i (g - g_i)^2}{3}}$$

(the factor  $1/2$  is converting the population standard deviation into error on the mean — dividing by the square root of the number of values contributing to the mean itself). The value of the gain is written to the bad pixel table header keyword `ESO DET OUT1 CONAD`, and its inverse to its header keyword `ESO DET OUT1 GAIN`.

An estimate of the RON could also be obtained from this linear fit, but while with this method the gain determination is accurate, the RON determination turns out to be very poor. For this reason in the *vmDET* recipe the RON is evaluated by directly measuring the variance of the signal within the overscan regions, as shown in Section 9.11.1.

#### 9.11.4 Bad pixels identification

The representative exposure level of each pair of flat fields with the same exposure time is determined as the median level of the 200 x 200 central region of the images. Then each pixel value from the same images is compared to the corresponding exposure levels. A pixel is flagged as “bad” when the slope of the linear fit of this table of values deviates from the expected slope by more than a given threshold.

The specified threshold is expressed in standard deviations from the mean value of the slopes. In order to apply this threshold correctly, and to determine what the expected slope is, the effects of the non-uniform illumination of the CCD are kept into account: an empirical (polynomial) model of the relation between the local illumination level with both the expected slope and the expected variance of the slope is determined by the recipe before applying the specified threshold.

The detected bad pixels are written to the bad pixel table columns and, if requested, as pixels of value 1 in a 0-filled image having the same size of the CCD (overscans are removed). For debug purposes, an error image containing the uncertainties on the fitted slopes can also be created.

It should be clear that with the described method any pixel that is not exposed (*e.g.*, because it belongs to a vignettted part of the CCD) would also be classified as “bad”, even if it is capable of a regular response.

### 9.12 vmbias

This recipe carries out the following fundamental steps:

1. Optional cosmic rays removal (see Section 9.2).
2. Combination of input bias frames (see Section 9.6).
3. Optional bad pixel cleaning from output master bias frame (see Section 9.1).

The details of each step are explained in the specified sections.

### 9.13 vmdark

This recipe carries out the following fundamental steps:

1. Bias subtraction (see Section 9.3).
2. Optional cosmic rays removal (see Section 9.2).
3. Combination of input dark frames (see Section 9.6).
4. Optional bad pixel cleaning from output master dark frame (see Section 9.1).

The details of each step are explained in the specified sections. The product master dark is divided by the total exposure time of all input darks (in seconds).

## 9.14 vmimflatscreen

This recipe carries out the following fundamental steps:

1. Bias subtraction (see Section 9.3).
2. Optional dark subtraction (see Section 9.4).
3. Optional cosmic rays removal (see Section 9.2).
4. Combination of input screen flat field frames (see Section 9.6).
5. Creation of master flat field as normalisation of the combined flat field.
6. Optional bad pixel cleaning from output flat field frames (see Section 9.1).

Beyond the standard reduction steps, described in some detail in the indicated sections, only the flat field normalisation procedure needs to be outlined here.

### 9.14.1 Screen flat field normalisation

The screen flat field is just used to determine the small-scale fixed-pattern-noise. Any possible large scale trend should be modeled and removed from the result frame, because it not only just reflects the characteristics of the instrument detector and optics, but also the typically non-uniform illumination of the screen by the calibration lamp. A good determination of the large scale trends would be obtained from a *sky* exposure, where a uniform field is actually observed — see Section 9.15.

A model of the large scale trends is obtained by first cleaning the bad pixels from the combined screen flat field (see Section 9.1, page 141) and then heavy smoothing the result. Next, the original combined flat field is divided by this smoothed version of itself, generating the master screen flat field. In symbols,

$$F = \frac{C}{\text{smooth}(C)}$$

where  $C$  is the combined screen flat field,  $F$  the master screen flat field, and *smooth* the smooth operator.

## 9.15 vmimflatsky

This recipe carries out the following fundamental steps:

1. Bias subtraction (see Section 9.3).
2. Optional dark subtraction (see Section 9.4).
3. Optional cosmic rays removal (see Section 9.2).
4. Combination of input sky flat field frames (see Section 9.6).

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5. Optional modeling of the large scale trends in the combined sky flat field, to be applied to the input master screen flat field.
6. Creation of the master sky flat field as simple normalisation of the combined flat field to its median value.
7. Optional bad pixel cleaning from output master sky flat field (see Section 9.1).

Beyond the standard reduction steps, described in some detail in the indicated sections, only steps 5 and 6 need to be outlined here.

### 9.15.1 Modeling large scale trends

This optional step is carried out when a master screen flat field was specified in the input SOF.

In general, the combination of the input frames is sufficient to produce an acceptable master sky flat field for use in the flat field correction of imaging science frames. However, in order to eliminate the contributions of field stars on the jittered sequence of sky flat fields, the frame combination method must be based on a rejection algorithm (rather than on a simple average). As a consequence, the combined master sky flat field tends to be noisier than a combined master flat field.

To solve this problem it is possible to use the small-scale information contained in a master screen flat field (see Section 9.14, page 151) and apply it to the more reliable large-scale trend of the combined sky flat field.

First, the combined sky flat field is divided by the master screen flat field, in order to eliminate the small-scale fixed-pattern-noise; next the bad pixels are cleaned (see Section 9.1, page 141), and a heavy smoothing is applied. The model of the large-scale trend obtained in this way is finally multiplied by the master screen flat field, resulting in a better quality combined sky flat field. In symbols,

$$S' = F \cdot \text{smooth}\left(\frac{S}{F}\right)$$

where  $S$  is the combined sky flat field,  $F$  the master screen flat field, *smooth* the smooth operator, and  $S'$  the improved combined sky flat field.

### 9.15.2 Combined flat field normalisation

The combined sky flat field, whatever way produced, is divided by its median level. The output is defined as the master sky flat field to be used in the reduction of science frames.



## 9.16 vmmasktocc

This recipe carries out the following fundamental steps:

1. Source detection on input pinhole image.
2. Matching mask pinholes with sources detected on the pinhole image.
3. Determination of the Mask to CCD transformation and its inverse.

A description of each step is given in the following sections.

### 9.16.1 Source detection

After applying the standard reduction steps (bias subtraction, flat fielding, cosmic rays and bad pixel cleaning if requested, etc.), the detection of the pinholes images on the CCD is made applying SExtractor [8] in PSF fitting mode. SExtractor is run twice: the first run is meant to determine the instrumental PSF (or, more precisely, the convolution of the pinholes shapes with the instrumental PSF) as a function of the CCD coordinates. A second SExtractor run is performed taking into account this PSF model.

### 9.16.2 Matching mask pinholes with their CCD images

The pinhole coordinates are read from the ADM included in the input image header, and transformed into CCD expected positions using the “first guess” Mask to CCD transformation. The actual position of a pinhole image on the CCD is searched within a given radius, and if more than one match is found then the brightest is chosen.

### 9.16.3 Determination of Mask to CCD transformations

A bivariate polynomial fit (see Section 8.2.1, page 133) is performed on pinholes mask positions vs detected positions on the CCD. First just a linear fit is tried, determining scale, offset, and rotation. Next a bivariate polynomial fit of the residuals is iterated a given number of times, rejecting at each iteration any detected position deviating more than 4· RMS from the model, until the Mask to CCD transformation is determined. The inverse transformation, from CCD to Mask, is obtained by inverse fit of the selected points.

## 9.17 vmskyccd

This recipe carries out the following fundamental steps:

1. Object detection on input astrometric image.
2. Matching stars with astrometric catalog entries.
3. Determination of Sky to CCD distortion.

A description of each step is given in the following sections.

### 9.17.1 Object detection

After applying the standard reduction steps (bias subtraction, flat fielding, cosmic rays and bad pixel cleaning if requested, etc.) the input astrometric field exposure is processed by SExtractor [8]. A table with the detected objects and their parameters is produced.

### 9.17.2 Star matching

All the stars are selected from the detected objects. Next, their CCD coordinates are transformed into celestial coordinates using the WCS and the “first guess” CCD to sky distortion model found in the header of the astrometric image (see Figure 8.2.1, page 135).

The applied CCD to sky distortion, used to transform real CCD pixels into virtual ones (see Section 8.2.2, page 134), is also corrected for temperature effects. Indicating with  $C_X(X, Y)$  the  $X$  component of the CCD to sky distortion model, the coordinate  $X_v$  of the virtual pixel is computed as

$$X_v = S(T) \cdot (C_X(X, Y) - X_c) + X_c$$

where  $X$  and  $Y$  are the real CCD coordinates,  $X_c$  is the central  $X$  coordinate of the CCD, and  $S(T)$  is the temperature correction factor given by

$$S(T) = k(T - T_m) + 1$$

where  $k = 6.0 \cdot 10^{-4}/^{\circ}C$  is the thermic expansion coefficient,  $T$  the beam temperature, and  $T_m$  the temperature at which the used “first guess” CCD to sky distortion model was evaluated. In the same way the

$$Y_v = S(T) \cdot (C_Y(X, Y) - Y_c) + Y_c$$

is applied.

After the objects celestial coordinates are computed, a match is made with the entries of the specified astrometric catalog, leading to a list of detected astrometric stars.

### 9.17.3 Determination of Sky to CCD distortions

Applying the WCS in the astrometric image header, the catalog celestial coordinates of the detected astrometric stars are transformed into CCD coordinates, and matched to their actual (*i.e.*, derived by SExtractor) coordinates on the CCD. A bivariate polynomial fit (see Section 8.2.2, page 134) is performed on theoretical positions vs real positions on the CCD, and vice versa, leading respectively to the Sky to CCD and the CCD to Sky distortion modeling.

The quality of the distortion modeling can be judged by the RMS of the model fit residuals, but most critical is the distribution of the astrometric stars on the field-of-view: it may happen that too few astrometric and badly distributed stars are available for a reliable fit. Such cases may be screened by a visual examination of

the astrometric image, but the computation of a uniformity index of the astrometric stars distribution on the field-of-view is helpful. (*To be done*).

## 9.18 vmimstandard

After applying the standard reduction steps (bias subtraction, flat fielding, cosmic rays and bad pixel cleaning if requested, etc.), this recipe carries out the following fundamental steps:

1. Object detection on input standard stars field image.
2. Matching stars with photometric catalog entries.

The object detection and the matching of the detected stars with the entries of a photometric catalog are carried out as in the recipe *vmiskyccd* (see Section 9.17, page 153). This recipe produces a table of the identified standard stars, with their positions, their catalog magnitudes in all the available bands, and their instrumental magnitudes (determined by SExtractor [8]). Further processing of an appropriate set of this kind of table (see for instance the recipe *vmimcalphot*, Section 7.9, page 86) would make possible to determine night zeropoints, atmospheric extinction coefficients, and colour terms.

## 9.19 vmimcalphot

This recipe is used to determine night zeropoints, atmospheric extinction coefficients, and colour terms from a set of star match tables, produced by the recipe *vmimstandard* (see Section 7.8, page 81). The input star match tables must all be derived from exposures made with the same filter.

In general this problem is solved by a robust minimisation of the linear system

$$Z - E \cdot A - C \cdot C_i = \Delta M_i$$

where, for a given star  $i$ ,  $\Delta M_i$  is the measured difference between the catalog magnitude and the instrumental magnitude in the appropriate band,  $C_i$  is the star colour index, and  $A$  is the airmass. The unknown terms are the atmospheric extinction coefficient  $E$  at the considered band, the colour term  $C$ , and the zeropoint  $Z$ .

However, it is also possible to derive a solution by freezing the values of either or both of the unknowns  $C$  and  $E$ ; while  $Z$  is always determined, freezing  $C$  would permit the determination of just the best coefficient  $E$  and vice versa. Freezing both  $C$  and  $E$  would determine  $Z$  as a simple estimate of  $\Delta M_i$  (plus an offset). Such cases, and in particular the last one, would typically be preferred in the case that just a small number of stars were available.

## 9.20 vmimpreimaging

This recipe is used to convert the instrument distortions (see Section 8.2.2, page 134) into the CO-matrix convention followed by the VIMOS mask preparation software (VMMPS). The distortions encoded in the computed CO-matrix include the temperature effects (see Section 9.17.2, page 154).

The conversion from the internal VIMOS convention to the CO-matrix convention is made using a regular 10x10 grid of CCD coordinates that are first transformed into celestial coordinates applying the distortion and transformation models found in the image header. The direct transformation from celestial to distorted CCD coordinates is then fitted by the CO-matrix model, using the appropriate functions of the SAO WCSTools package [10].

This recipe also applies to the input image the same data reduction steps applied by the recipes *vmimstandard* and *vmimobsstare*, excluding the source detection task [8]. The magnitude zeropoint from a given photometric table might also be added to the reduced image header.

## 9.21 vmimobsstare

This recipe is used to reduce a single scientific exposure in direct imaging mode, and it carries out the following fundamental steps:

1. Bias subtraction (see Section 9.3).
2. Optional dark subtraction (see Section 9.4).
3. Flat field correction (see Section 9.5).
4. Optional bad pixel cleaning (see Section 9.1).
5. Optional cosmic rays removal (see Section 9.2).
6. Source detection (running SExtractor).

The details of each step are explained in the specified sections. About the source detection task, please refer to the SExtractor documentation [8], that can be found at

[http://terapix.iap.fr/rubrique.php?id\\_rubrique=91/index.html](http://terapix.iap.fr/rubrique.php?id_rubrique=91/index.html).

## 9.22 vmimobsjitter

This recipe is used to reduce a sequence of scientific exposures obtained in direct imaging mode, and to align and sum the results in a combined frame. The data reduction steps applied to each frame are the same applied in recipe *vmimobsstare*. The only difference lays in the final frames combination, that consists of the following fundamental steps:

1. Determine a common pixelisation and coordinate system for the combined frame.
2. Resample the single reduced frames to the new pixelisation.
3. Combination of the resampled frames (see Section 9.6).

A description of the first two steps is given in the following sections.

### 9.22.1 Determination of common coordinate system and pixelisation

The common coordinate system and pixelisation for the combined frame are simply those of the first frame of the input sequence. The range of celestial coordinates covered by the union of all the input images is determined, and the pixel range of the first frame is expanded accordingly.

### 9.22.2 Resampling of reduced frames

For each single reduced image, an output image with the common coordinate system and pixelisation defined above is allocated. The coordinates of each pixel of the output frame are converted to celestial coordinates using the common WCS, and then converted to the pixel coordinates of the input image, using its specific WCS.<sup>19</sup> The interpolated value of the nearby pixels — 4 pixels for bilinear and 16 for bicubic interpolation — is computed, and written to the running pixel position of the output image. Coefficients and formulae for the bi-cubic interpolation are taken from “Numerical Recipes”, II Ed., page 119.

## 9.23 vmspflat

This recipe carries out the following fundamental steps:

1. Creation of the combined flat field from the input raw flat field exposures.
2. Creation of the normalised master flat field from the combined flat field.

A description of each step is given in the following sections.

### 9.23.1 Creation of the combined flat field

After applying the standard reduction steps (bias subtraction, bad pixel cleaning if requested, etc.), the input MOS flat field images are stacked together according to the specified frame combination method (see Section 9.6, page 143).

### 9.23.2 Normalisation of the combined flat field

The combined flat field normalisation is carried out in four steps. First, each slit spectrum is extracted and remapped removing the spatial curvature; then it is heavily smoothed (with a filter or with a polynomial fit); the smoothed result is mapped back to its original reference; and finally the combined flat field image is divided by the image of smoothed spectra.

The result is the master flat field, that may be used by other data reduction recipes for applying a flat field correction.

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<sup>19</sup>It is well known that an alignment of the input images based solely on the images WCSs is not sufficiently accurate, and the described algorithm still needs to be improved in this respect. Preliminary tests have also indicated that the image alignments obtained with this recipe tend to be more inaccurate at larger offset between images. Work is in progress to solve these problems.

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The spectral optical and curvature models are necessary for a correct remapping of the spectra during the smoothing operation. For this purpose the “first guess” of the  $x$  component of the optical distortion model is improved, together with the “first guess” of the spatial curvature model, by tracing the edges of the slit spectra and fitting the found positions (see Section 8.3.3). The  $y$  component of the optical distortion model cannot be determined, because flat field spectra do not offer any landmark along the dispersion direction. For this reason the optical and the curvature distortion models derived with *vmisflat* cannot be considered consistent with the wavelength calibration determined with *vmispcaldisp*, and therefore cannot be used for any other purpose (including writing them to the VIMOS IWS configuration files).

A more detailed description of the spatial curvature determination is given in Section 9.24.3.

## 9.24 vmispcaldisp

This recipe carries out the following fundamental steps:

1. Creation of the combined arc lamp frame from the input raw arc lamp exposures.
2. Determination of the spectral optical distortion model from the combined arc lamp exposure.
3. Determination of the spatial curvature from the combined master flat field (if given: see Section 7.14).
4. Determination of the inverse dispersion solution.

A description of each step is given in the following sections.

### 9.24.1 Creation of the combined arc lamp frame

This operation is performed in the same way as for the creation of the combined flat field described in Section 9.23.1.

### 9.24.2 Determination of the optical distortion model

The  $x$  and the  $y$  components of the optical distortion models are determined by a bivariate polynomial fit of a list of corresponding mask and CCD positions (see Section 8.3.2).

To determine the CCD position of the reference wavelength  $\lambda_o$  corresponding to the coordinates  $(x, y)$  of the centre of a slit on the mask, a template of the expected pattern of lines in the close neighbourhoods of the reference wavelength position is built (see Figure 9.24.1).

The template (typically consisting of a pattern of 3–5 lines) is tried at different CCD positions around the expected position derived from the “first guess” optical distortion model, searching for a maximum match. To avoid flat maxima in the search of the best  $X$  coordinate, the pattern is also made as wide as the slit width on the CCD. The search is repeated at slightly different values of the dispersion (around the one expected at the position of the reference wavelength), to make the search robust against possible slight changes of the instrument distortions.

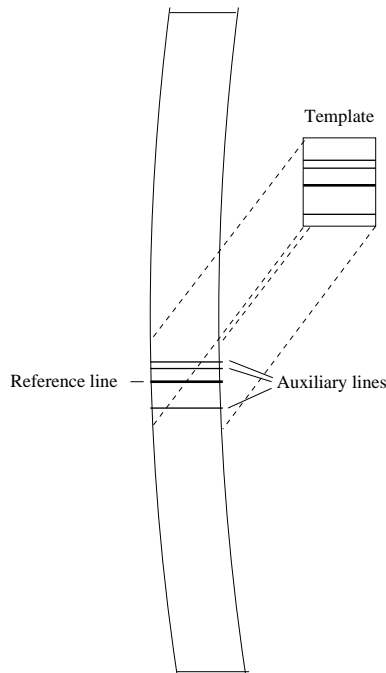


Figure 9.24.1: *Pattern matching for optical distortion model determination.*

The pattern matching search is repeated for each slit of the mask, and when the list of matching mask and CCD coordinates is completed a new optical distortion model can be fit.

An optical distortion model fit is not performed if there are not enough slits: the number of slits must be at least twice the number of free model parameters. In addition to that, the slits coordinates on the mask must span at least  $50\text{ mm}$  both in the  $x$  and in the  $y$  direction. If these conditions are not met, then the “first guess” optical distortion model is left untouched, and used “as is” in the remaining reduction steps.

### 9.24.3 Determination of the spatial curvature model

If a combined flat field is passed to *vmcpcaldisp*, then the spatial curvature “first guess” model can be improved. The procedure is identical to the one applied in the *vmcflat* recipe, but the curvature model derived with *vmcpcaldisp* is different because it is based on a better optical distortion model determination.

The spatial curvature model is refined starting from its “first guess”, used in combination with the just derived optical distortion model. The edges of all the slit spectra are located and traced in the combined master flat, and are fit by a polynomial shape. Currently a second degree polynomial is used for this purpose. The *global* spatial curvature model is then determined by fitting the values of all the coefficients of all the local polynomials, as a function of the position  $(x, y)$  of the slits ends on the mask. The bivariate polynomial used in the fit has currently 2x2 free coefficients.

For details on the polynomials used in the spatial curvature modeling, see Section 8.3.3.

A spatial curvature model fit is not performed if there are not enough slits: the number of slits must be at least

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twice the number of free model parameters. In addition to that, the slits coordinates on the mask must span at least 50 *mm* both in the *x* and in the *y* direction. If these conditions are not met, then the “first guess” curvature model is left untouched, and used “as is” in the remaining reduction steps.

#### 9.24.4 Determination of the inverse dispersion solution

Each CCD pixel laying on the image of a slit main axis (corresponding to the spectrum reference wavelength) is used as a starting point in extracting a 1D-spectrum. Such extraction is performed following the spatial curvature model, that for each CCD pixel defines a *row* on the slit spectrum (see Figure 8.3.1, page 138).

As an *optional* preliminary step in the determination of the inverse dispersion relation, the spectrum corresponding to the central row of the slit is extracted. Next, a template of the arc lamp spectrum is created from the line catalog: the template consists of a list of wavelength intervals, each centred around a catalog wavelength and with a size depending on the slit width. When different windows overlap, they are merged into a single wavelength interval.

The extracted central spectrum is then compared to the arc lamp template, attempting to pre-tune the local solution derived from the “first guess” global IDS. The pre-tuning operation is performed in the following steps:

1. The logarithm of the extracted spectrum is computed.
2. The first guess polynomial relation between  $\lambda$  and  $Y$  CCD pixel is extracted from the “first guess” global IDS. A grid of sampling values is defined for the coefficients of this polynomial (currently the only modified coefficients are the constant term and the dispersion, *i.e.*, the coefficients  $d_o$  and  $d_1$  defined in Section 8.3.4).
3. Using the polynomial corresponding to each node of the grid of coefficients values, the arc lamp template is transformed into pixel intervals on the extracted spectrum.
4. The logarithm of the extracted spectrum is integrated in the pixel intervals obtained at point 3. The result of this integral is used as a *match index*.
5. The polynomial having the coefficients corresponding to the the highest match index is selected, replacing the header “first guess” for the examined slit.

Once the “first guess” polynomial is pre-tuned, it is used to correctly identify the arc lamp lines in all slit spectra, and to determine their accurate position.

The line identification is done by selecting on the extracted spectrum the peak which is closest to its expected position. The position of the identified line is determined by a peak search algorithm run within a window of given size (see Section 7.14).

An alternative way to identify lines is provided, the so-called *blind* method, that doesn’t need any first-guess IDS model, being based on pattern recognition. This method is described in some detail in Section 9.7, page 144.

Once a table of identified lines positions is completed for the extracted spectrum, a polynomial transformation from catalog wavelength to pixel position is determined. Typically the polynomial transformation is of  $3^{rd}$



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order for low dispersion grisms, and  $4^{th}$  order for higher dispersion grisms (see Section 8.3.4). This process is repeated for each row of each slit of the mask, and all the solutions are written to the output extraction table (see Table 7.14.3, page 103).

The global IDS model is determined by the bivariate polynomial fitting of the coefficients of the local polynomials, as described in Section 8.3.4. Currently this model has 3x3 free parameters.

An inverse dispersion solution is not determined if there are not enough slits: the number of slits must be at least twice the number of free model parameters. In addition to that, the slits coordinates on the mask must span at least 50 *mm* both in the *x* and in the *y* direction. If these conditions are not met, then the “first guess” global IDS is left untouched, and used “as is” in the remaining reduction steps.

Plots of arc lamp spectra from different grisms and lamps combinations are given in Figures 9.24.2–9.24.10, where the spectral lines used in the wavelength calibration are marked.

A list of all the used calibration lines available from the Helium, Argon and Neon lamps within the spectral range of all the VIMOS grisms is given in tables 9.24.1 and 9.24.2.

Wavelength (Å)	Element	Note
3888.650	He	
4026.190	He	
4471.480	He	
4713.143	He	
4921.929	He	
5015.675	He	
5400.560	Ne	
5764.418	Ne	
5852.488	He	
5875.618	He	
5944.834	Ne	
6029.997	Ne	
6074.338	Ne	
6096.163	Ne	
6143.062	Ne	
6163.594	Ne	
6217.281	Ne	
6266.495	He	
6304.789	Ne	
6334.428	Ne	
6382.991	Ne	
6402.246	Ne	
6506.528	Ne	
6532.882	Ne	
6598.953	Ne	
6678.150	He	
6678.200	He+Ne	blend 6678.150 + 6678.280
6678.280	Ne	
6717.043	Ne	
6929.468	Ne	
6965.430	Ar	
7032.413	Ne	
7065.188	He	
7173.939	Ne	
7245.167	Ne	

Table 9.24.1: Arc lamp calibration lines available in the VIMOS spectral range (continued in Table 9.24.2).

Wavelength (Å)	Element	Note
7272.936	Ar	
7281.349	He	
7383.980	Ar	
7438.899	Ne	
7488.872	Ne	
7503.867	Ar	
7507.000	Ar	blend 7503.867 + 7514.651
7514.651	Ar	
7535.770	Ne	
7544.046	Ne	
7635.105	Ar	
7723.800	Ar	blend 7723.76 + 7724.21
7948.175	Ar	
8006.156	Ar	
8012.000	Ar	blend 8006.156 + 8014.786
8014.786	Ar	
8103.692	Ar	
8110.000	Ar	blend 8103.692 + 8115.311
8115.311	Ar	
8264.521	Ar	
8300.326	Ne	
8377.607	Ne	
8408.210	Ar	
8415.000	Ar	blend 8408.210 + 8424.647
8424.647	Ar	
8495.360	Ne	
8521.441	Ar	
8634.648	Ne	
8654.383	Ne	
8667.943	Ar	
8780.622	Ne	
8853.866	Ne	
9122.966	Ar	
9224.500	Ar	
9657.780	Ar	

Table 9.24.2: (Continued from Table 9.24.2) Arc lamp calibration lines available in the VIMOS spectral range.

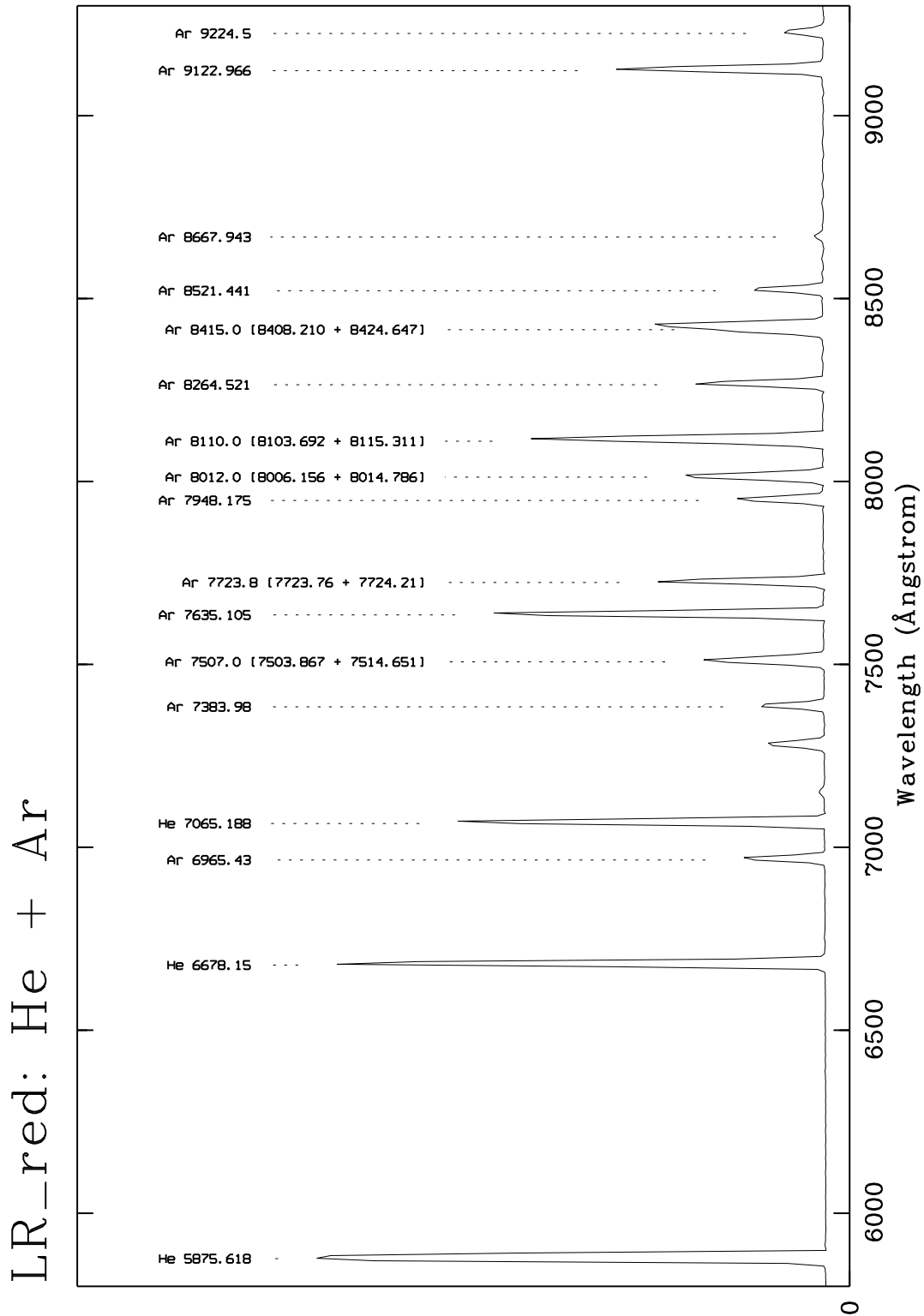


Figure 9.24.2: LR red arc line spectrum from 5800 to 9300 Ångstrom. The lines used for calibration are indicated.

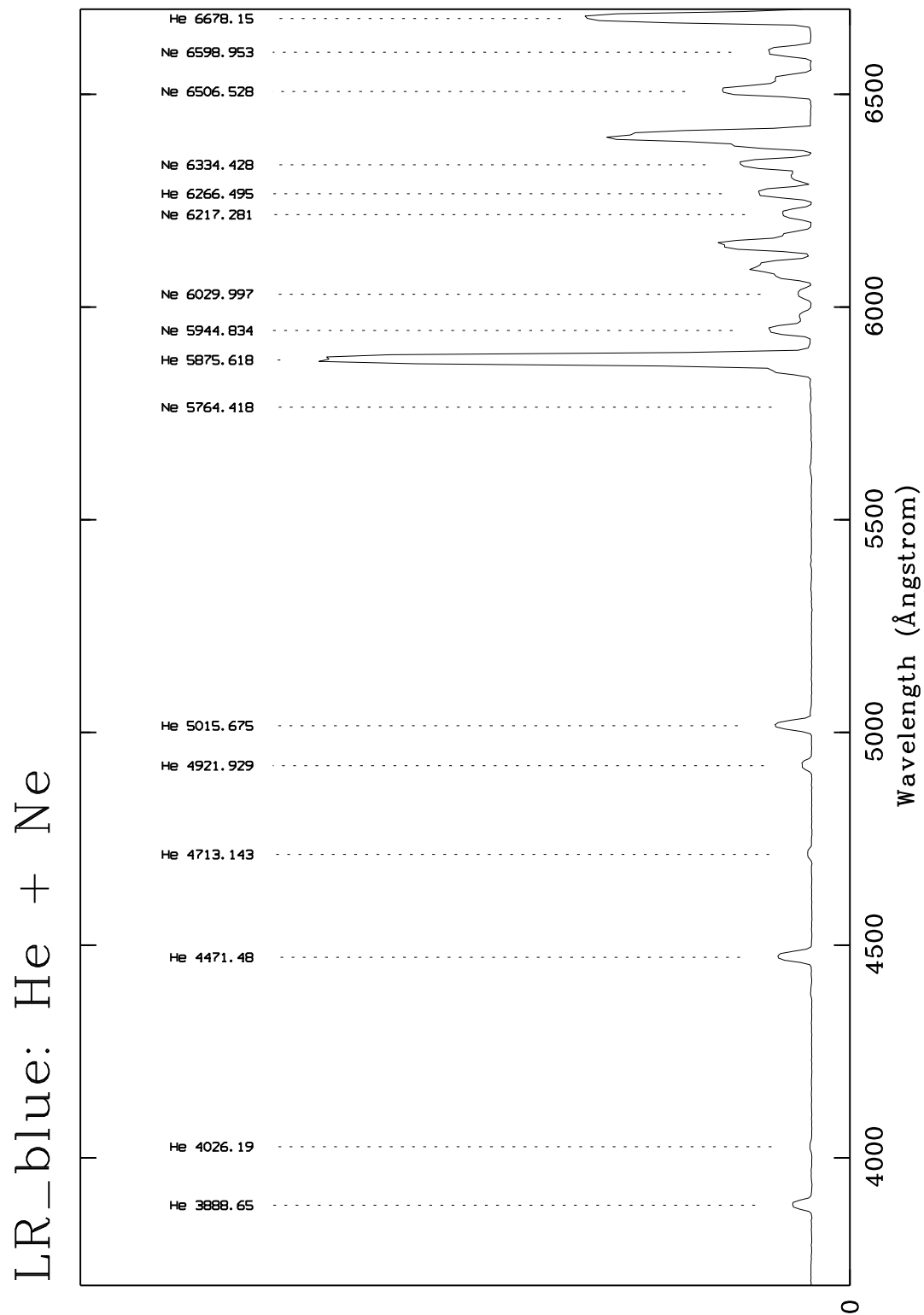


Figure 9.24.3: *LR blue arc line spectrum from 3800 to 6750 Ångstrom. The lines used for calibration are indicated.*

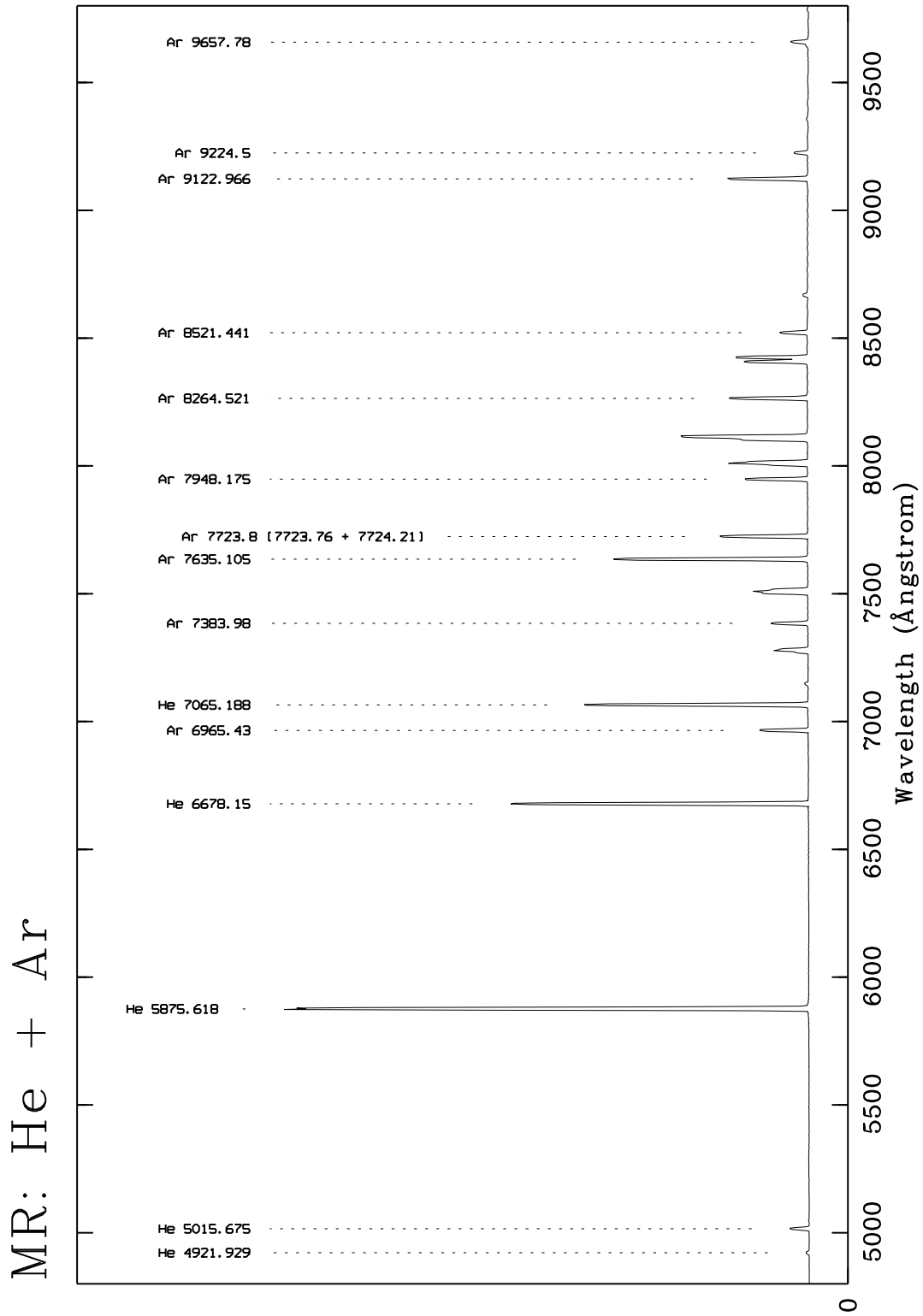


Figure 9.24.4: MR arc line spectrum from 4800 to 9800 Ångstrom. The lines used for calibration are indicated.

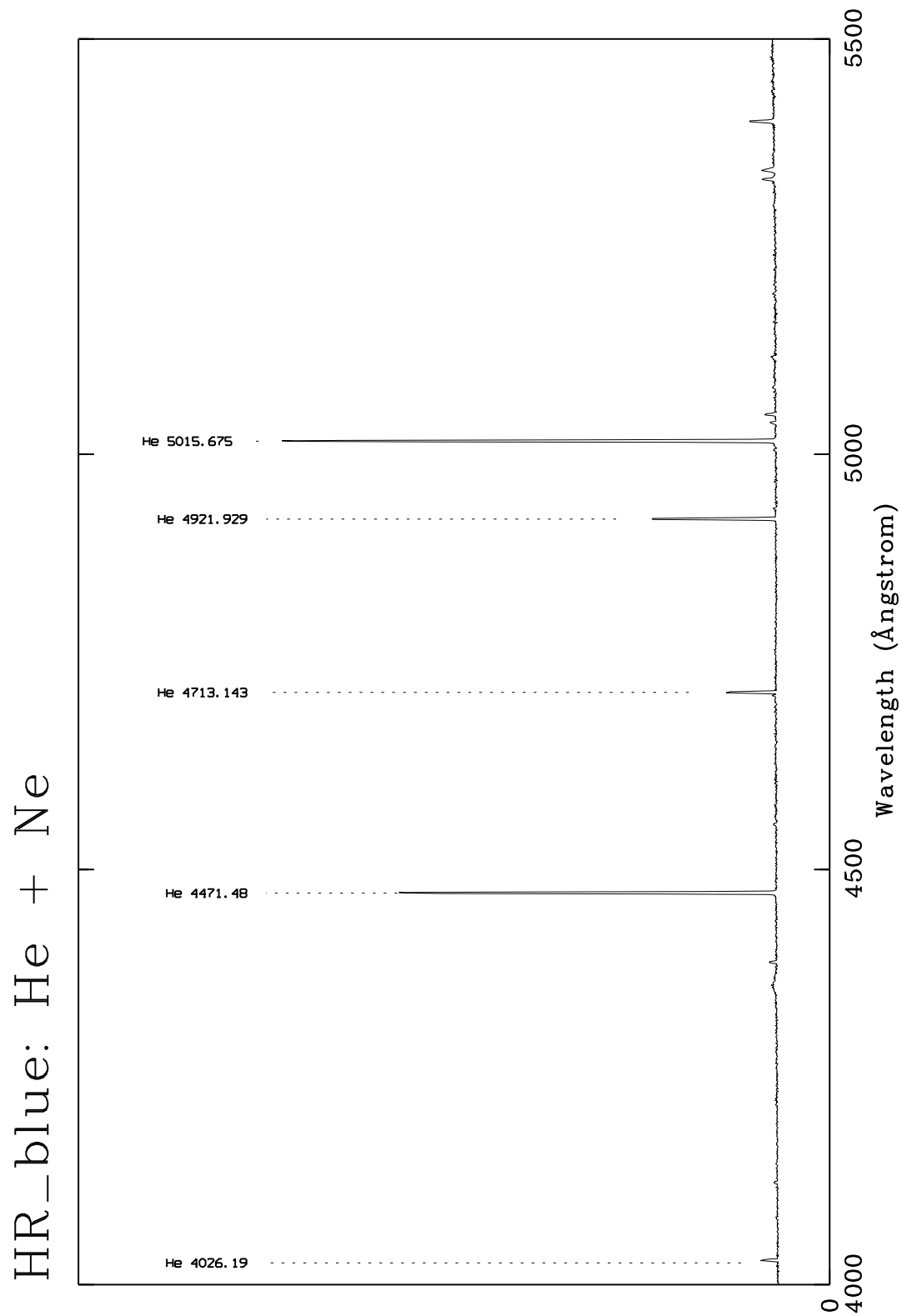


Figure 9.24.5: *HR blue arc line spectrum from 4000 to 5500 Ångstrom. The lines used for calibration are indicated.*

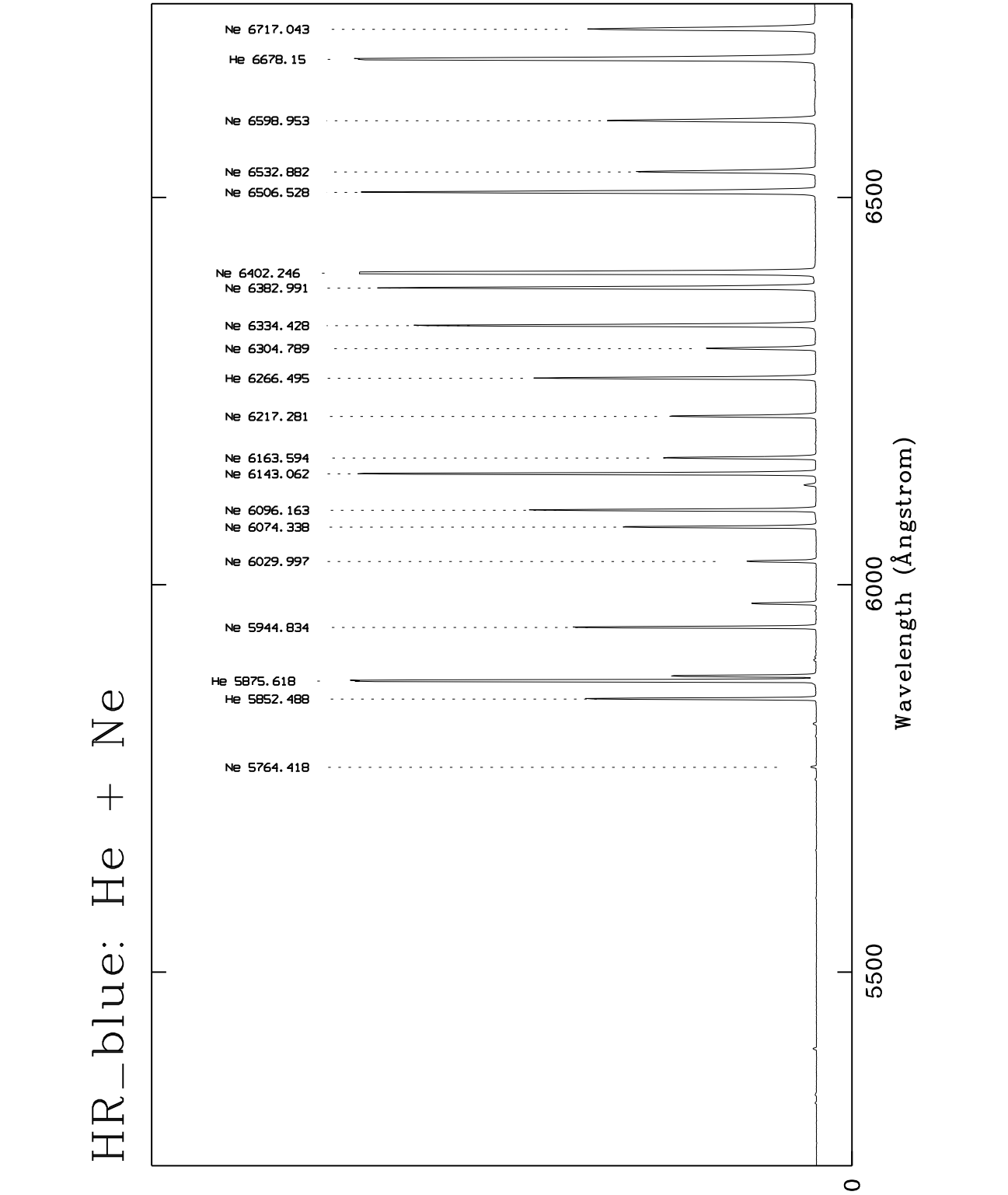


Figure 9.24.6: *HR blue arc line spectrum from 5250 to 6750 Ångstrom. The lines used for calibration are indicated.*



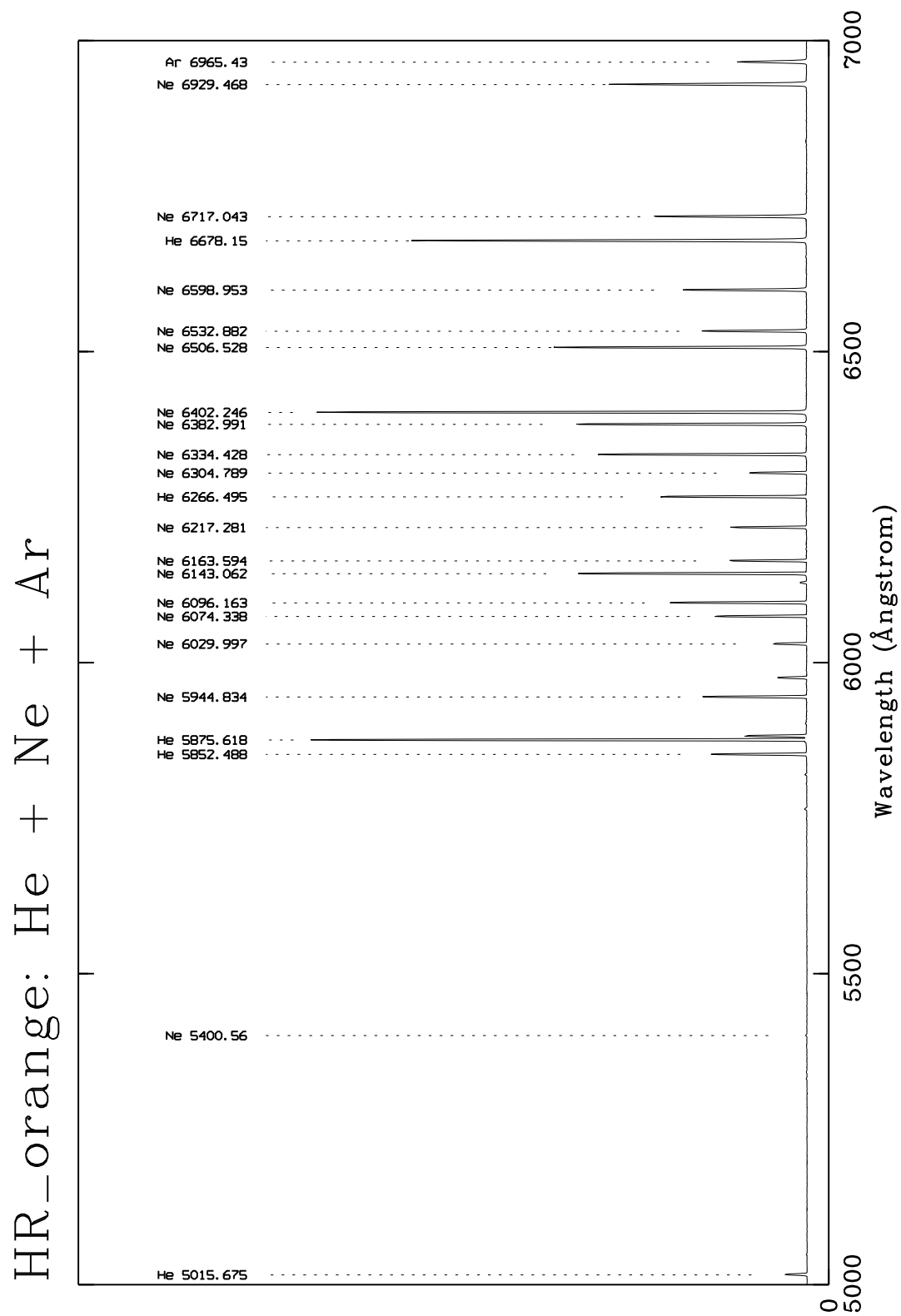


Figure 9.24.7: *HR orange arc line spectrum from 5000 to 7000 Ångstrom. The lines used for calibration are indicated.*

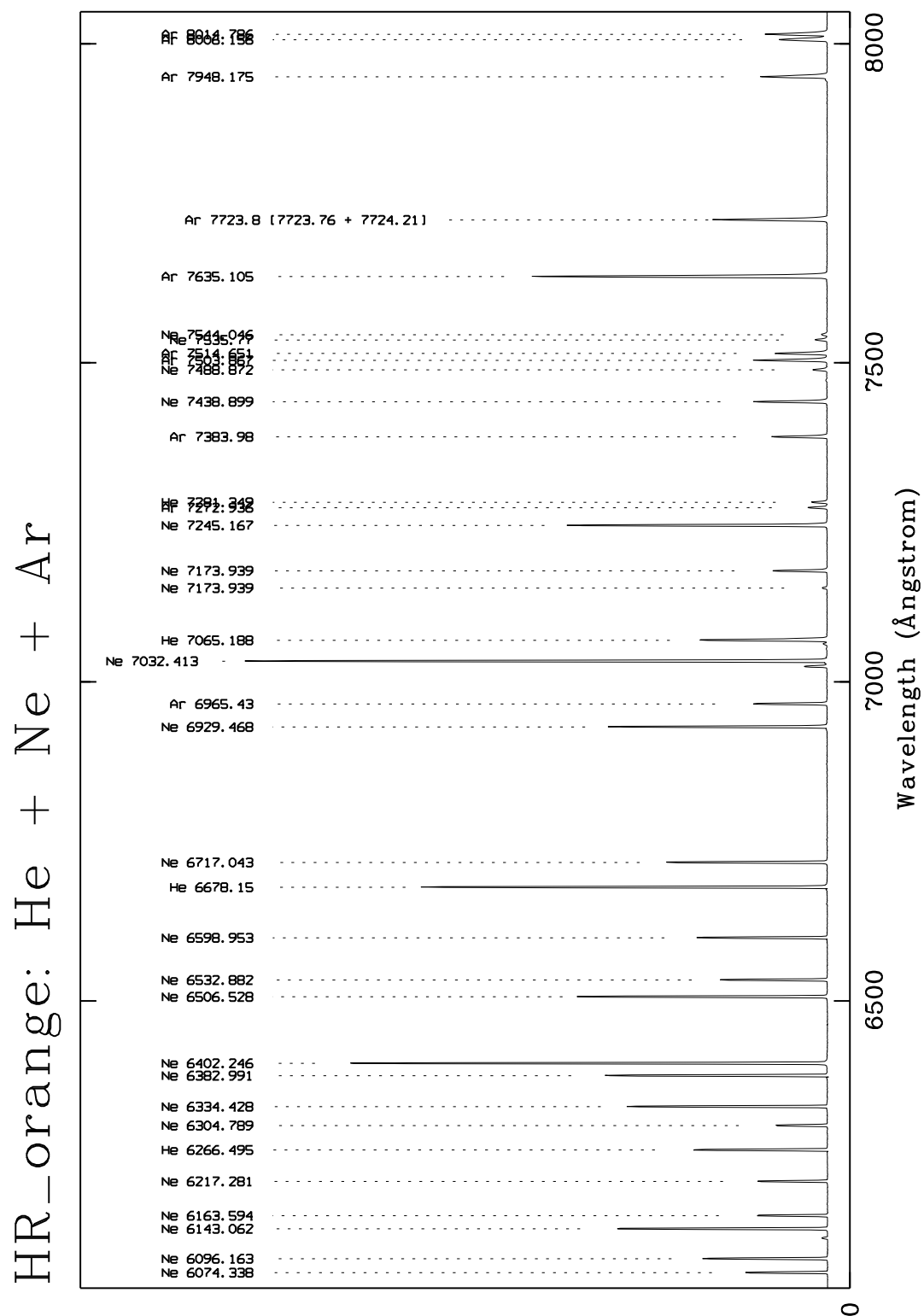


Figure 9.24.8: *HR orange arc line spectrum from 6050 to 8050 Ångstrom. The lines used for calibration are indicated.*

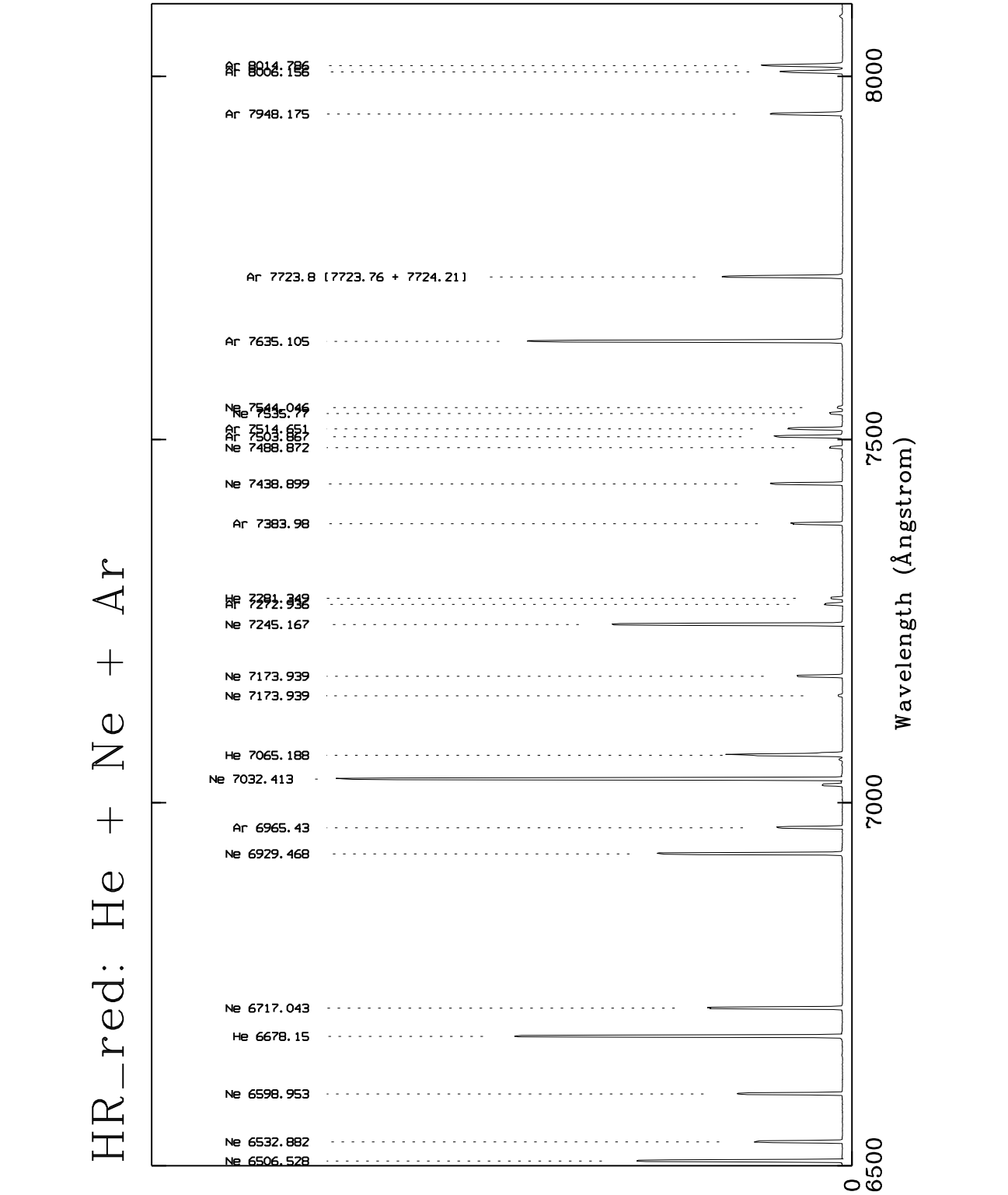


Figure 9.24.9: *HR red arc line spectrum from 6500 to 8100 Ångstrom. The lines used for calibration are indicated.*

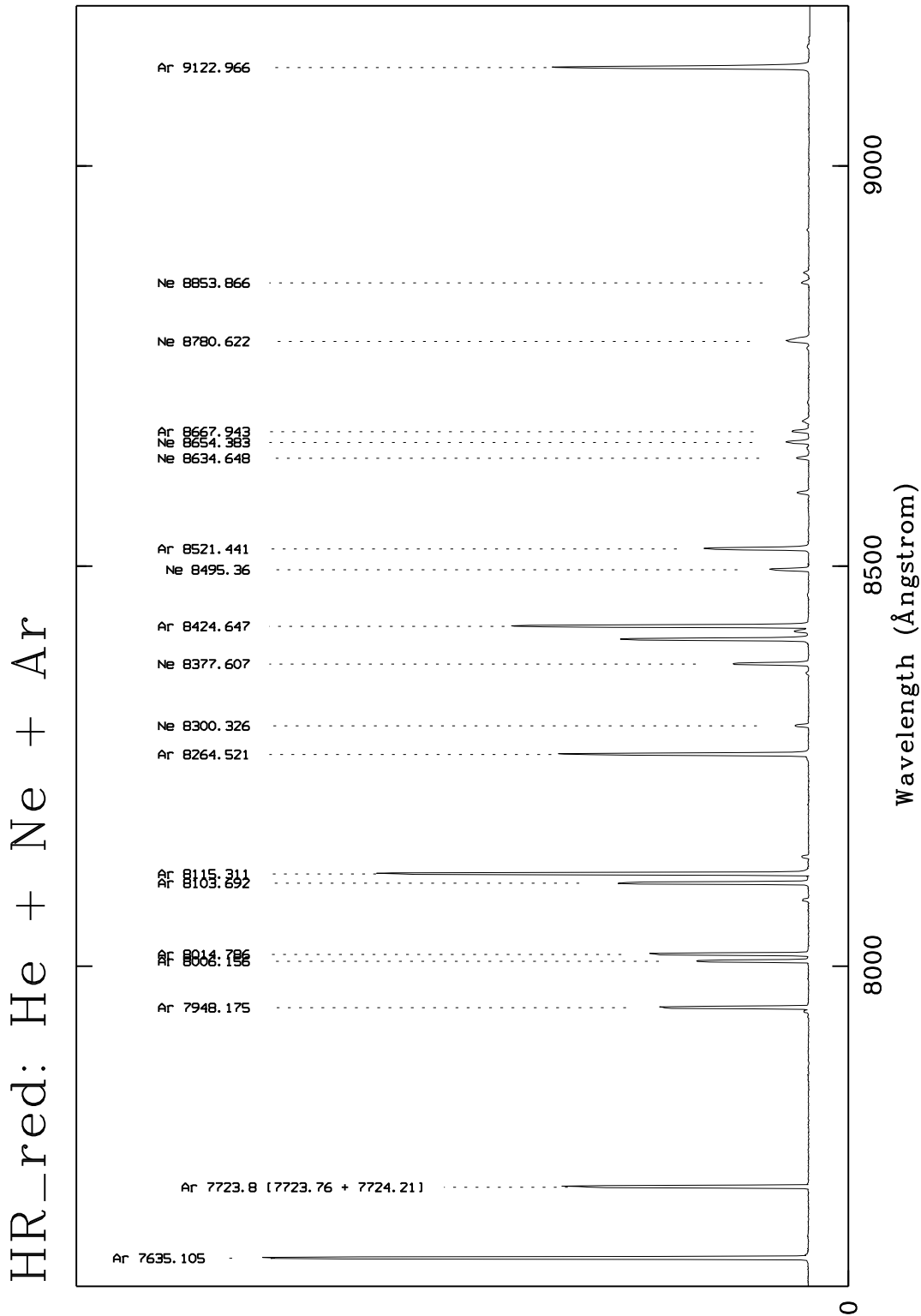


Figure 9.24.10: *HR red arc line spectrum from 7600 to 9200 Ångstrom. The lines used for calibration are indicated.*

## 9.25 vmmosobsstare

This recipe is used to reduce one exposure made in MOS mode. The following fundamental steps are carried out:

1. Bias subtraction (see Section 9.3).
2. Optional dark subtraction (see Section 9.4).
3. Optional flat field correction (see Section 9.5).
4. Optional bad pixel cleaning (see Section 9.1).
5. Align distortion models to sky lines positions.
6. Slit spectra extraction.
7. Object detection.
8. Sky modeling and subtraction from extracted slit spectra.
9. Object extraction.
10. Flux calibration of extracted spectra (see Section 9.10).

Beyond the standard reduction steps, described in some detail in the indicated sections, only the last five steps need to be outlined here.

### 9.25.1 Align distortion models to sky lines positions

A set of sky lines, dependent of the spectral range covered by the grism in use, is taken as reference for aligning the spectral distortion models to a possible variation of the instrument mechanical flexures. For each slit spectrum, the distortion models derived from the calibration data are used to look for the reference sky lines around their expected positions along the spectral dispersion direction. The median offset between the expected and the observed positions is added to the  $Y$  component of the optical distortion model (see Section 8.3.2, page 136), that will be then used in the extraction of the slit spectra.

### 9.25.2 Slit spectra extraction

Each slit spectrum is read from the pre-processed input image, following the shapes of the modeled spectral distortions (see Section 8.3.5). The slit spectra are always resampled along the cross-dispersion direction at a 1-pixel step, and along the dispersion direction at the wavelength step defined by the keyword `PRO WLEN INC` of the used grism table, ensuring that the flux is conserved. The resampled values are written to an output image that contains all the rectified slit spectra aligned in wavelength (with slit 1 at bottom).

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### 9.25.3 Object detection

After the slit spectra are all extracted and rectified, a detection algorithm is run to locate the emission of possible objects. The mean spatial profile of each slit spectrum is computed in the wavelength range specified in the used grism table (see Section 7.15, page 108), excluding cosmic ray events. The profile is analysed, looking for signal significantly above the background noise.

The background level and its associated noise are determined empirically, computing iteratively a robust estimate of the most probable value in the profile, and excluding at each iteration all values with positive residuals greater than their population RMS. The final population RMS is taken as the noise level.

All the profile values exceeding the background level by a specified number of noise sigmas are selected. Each unbroken sequence of selected profile values is taken as an object candidate. If a sequence of values is shorter than a specified amount (see parameter *MinObjectSize*, Table 7.15.5, page 111) it is rejected. If a sequence of values is longer than another specified amount (see parameter *MaxObjectSize*), an attempt is made to unblend the object into sub-objects, that will be then extracted separately. The unblending operation is made using a watershed algorithm to analyse the structure of the sub-profile and to reassign portions of the sequence to the identified sub-objects.

### 9.25.4 Sky modeling

Once the positions of the detected objects on the extracted and rectified slit spectra are determined, it is possible to analyse the values of the sky pixels to estimate the sky level within the regions containing the objects. For each wavelength, the median sky level may be computed and replaced in the objects regions or, alternatively, a polynomial fit may be tried on the sequence of available sky values, and the interpolated values used at the object positions. In all cases, the sky values — real or computed — are subtracted from the extracted slit spectra.

### 9.25.5 Object extraction

The object spectra are extracted from the rectified and sky subtracted slit spectra. The method used may be a simple aperture extraction, where all the signal included in the object region is integrated, or, alternatively, an optimal extraction, *i.e.* an average of the signal optimally weighted by a function of the signal noise. The optimal extraction takes also care of removing the cosmic rays contamination, and resolves the possible effects of a residual spatial curvature. The algorithm used is the one described by K.Horne (1986), in PASP vol.98, p.609. It should be noted that this method is not suitable for extended or blended objects, or for objects only consisting of emission lines (with no continuum), where the object profile might not be modeled properly.

While the aperture extraction is applied to the regions obtained by the object detection task and specified in the window table (see table 7.15.3, page 109), the optimal extraction is applied to a region having twice that size, provided that this wouldn't exceed the slit boundaries.

## 9.26 vmmosobsjitter

This recipe is used to reduce a sequence of exposures made in MOS mode. The following fundamental steps are carried out for each input frame:

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1. Bias subtraction (see Section 9.3).
2. Optional dark subtraction (see Section 9.4).
3. Optional flat field correction (see Section 9.5).
4. Optional bad pixel cleaning (see Section 9.1).
5. Align distortion models to sky lines positions (see Section 9.25.1).
6. Slit spectra extraction (see Section 9.25.2).
7. Object detection (see Section 9.25.3).
8. Sky modeling and subtraction from extracted slit spectra (see Section 9.25.4).

The following steps involve all the images containing the extracted and sky subtracted slit spectra:

1. Align and combine the processed images.
2. Iterate the object detection on the combined image (see Section 9.25.3).
3. Object extraction from the combined image (see Section 9.25.5).
4. Flux calibration of extracted spectra (see Section 9.10).

Beyond the reduction steps described in some detail in the indicated sections, only the image alignment needs to be outlined here.

### 9.26.1 Align and combine the processed images

The object detection task applied separately to each processed frame is expected to lead to the detection of a number of objects (at least the brightest ones). Their positions are then correlated between images, leading to the determination of a median offset valid for each exposure relatively to the first exposure of the jittered sequence. The images are aligned and resampled accordingly, before being combined using a median combination method (see Section 9.6).

## 9.27 vmmosstandard

The data reduction steps applied by this recipe are the same as those applied by the *vmmosobsstare* recipe. The only extra operations is the determination of the efficiency and response curves as described in section 9.9.

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## 9.28 Overview of the VIMOS IFU data reduction procedure

In this section, an overview of the IFU data reduction procedure is given. This procedure is not yet completed in the current pipeline release, and it needs further testing for evaluating its robustness and reliability. The distributed IFU pipeline recipes should be considered as a beta release offered for evaluation to a wider community of users.

### 9.28.1 Required data

For the described data reduction three different types of exposures are required:

- Flat field lamp exposure
- Arc lamp exposure
- Science exposure

where it is assumed that all the datasets have been bias subtracted (see Section 9.3, page 143).

The data reduction strategy is based on the idea of aligning the tracings of the flat field spectra directly to the tracings of the brightest science spectra. This alignment would compensate the traslation and the rotation of the spectra caused by the instrument mechanical instabilities, making it possible to optimally extract all the scientific spectra. In general the flexure component along the dispersion direction would not be accurately determined in this way (for geometrical reasons), but this is then solved by aligning the wavelength calibration obtained from the arc lamp exposure to the sky lines in the science exposure, or by applying a model of the instrument flexures along the dispersion direction.

This method is advantageous because it does not require any calibration to be taken during the night. Data reduction would be possible with flat field and arc lamp exposures obtained at daytime, provided that the following conditions are fulfilled:

1. The instabilities of the instrument (flexures) and of the IFU mask (mechanical play) would never introduce offsets larger than 2 pixels on the spectra positions on the CCD.<sup>20</sup>
2. At least one spectrum of the science exposure should be traceable (with the current method a spectrum begins to be safely traceable when the signal reaches 50 e<sup>-</sup>/pixel).

A second strategy may be applied in the unfortunate case that no science spectra are traceable. In such a situation the alignment of the flat field tracings to the science could only be based on other sources. For instance, an arc lamp exposure may be obtained before and after the scientific observation. The two exposures would be correlated to obtain the differential flexure, and then the standard tracing solution from the day flat field calibration would be aligned to the mean flexure position obtained. In the current data reduction system this method is not yet implemented, and when no traceable scientific spectra are available the extraction mask obtained from the flat field exposure is used without alignment.

<sup>20</sup>As of today (May 2005) this condition is not yet fulfilled, and therefore night calibrations are still mandatory.



### 9.28.2 Fibers identification

Please refer to Section 4.5, page 19, for the conventions used in numbering the IFU components.

By fibers identification we mean here the correct association of a fiber position on the IFU mask to a corresponding position on the CCD. If a conventional  $Y_o$  coordinate (*i.e.*, measured along the dispersion direction) is chosen on the CCD, the fiber identification would consist of assigning to each fiber its  $X$  position along this reference line (see Figure 9.28.1).

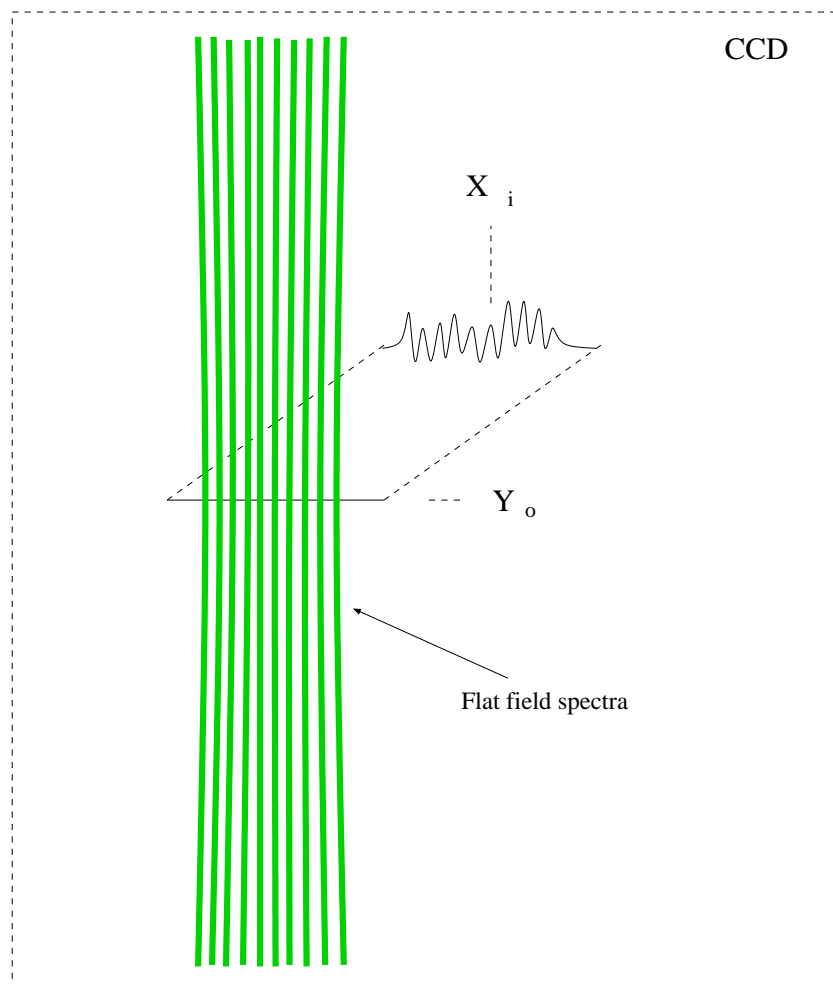


Figure 9.28.1: *The reference  $Y_o$  coordinate in the fiber identification procedure is conventionally fixed.*

Such an identification is given even in the case a fiber is not visible, either because it is damaged, or lost in the vignetted part of the CCD, or even purposefully masked.

The fiber spectra identification is always carried out on a flat field exposure. Preliminary identifications, performed manually on a set of reference flat field exposures (one for each grism/quadrant combination), are available in the calibration directory. Such safe identifications are used as reference and transferred to any other flat field by cross-correlation. With this method it is possible to safely identify fibers even in presence of major

instabilities of the instrument (currently the correlation radius is set to 10 pixels).

Alternatively fibers may be even identified without any first-guess on the CCD position of the fiber signal. This blind fibers identification is based on a folding analysis on the reference row of the input IFU flat field exposure, to roughly determine the position of the gaps between blocks. This method safely rejects false gaps due to IFU head masking, dead fibers, and bad CCD columns. After the positions of the gaps are determined, a correlation of each 80-fibers block with a grid of 80 5-pixel-spaced points is performed, leading to the final identification of the fibers within each block.

The blind fiber identification would not be bullet-proof in the case that either the first or the last fiber block is cut by the vignetted part of the CCD. Rather, the ambiguity introduced by the possible loss of fibers at the other end of the block would be inherent to the data, and there would be no way to safely identify the visible fibers (but by a judgment *a posteriori* on the quality of the reduced data).

Both the described methods are applicable by recipe `vmifucalib` (see Section 7.19, page 120).

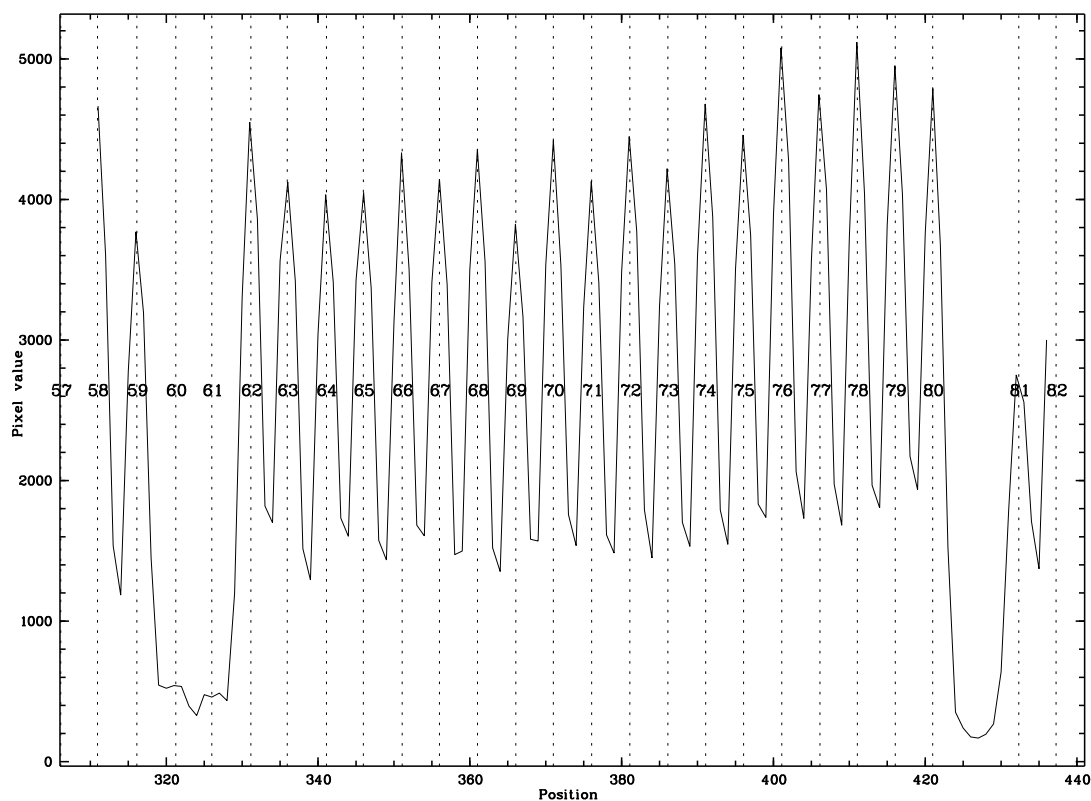


Figure 9.28.2: Fiber identification along the cross-dispersion direction. The gap between the first and the second blocks of fibers is visible on the right. On the left the positions of two fibers lost to the IFU head shutter are marked.

### 9.28.3 Tracing spectra

The tracing of each fiber flat field spectrum is a relatively simple matter, given the typically high S/N ratio reached in flat field exposures. The start  $X$  positions for the tracing, at a conventional  $Y_o$  coordinate on the CCD, are those obtained by the fiber identification task (see Section 9.28.2, page 177). Such positions are then used as first-guesses for the peak positions at the  $Y_o + 1$  and  $Y_o - 1$  coordinates, that are respectively used as first-guesses for the  $Y_o + 2$  and  $Y_o - 2$  coordinates, and so on, till some predefined limits set for spectral extraction are met.

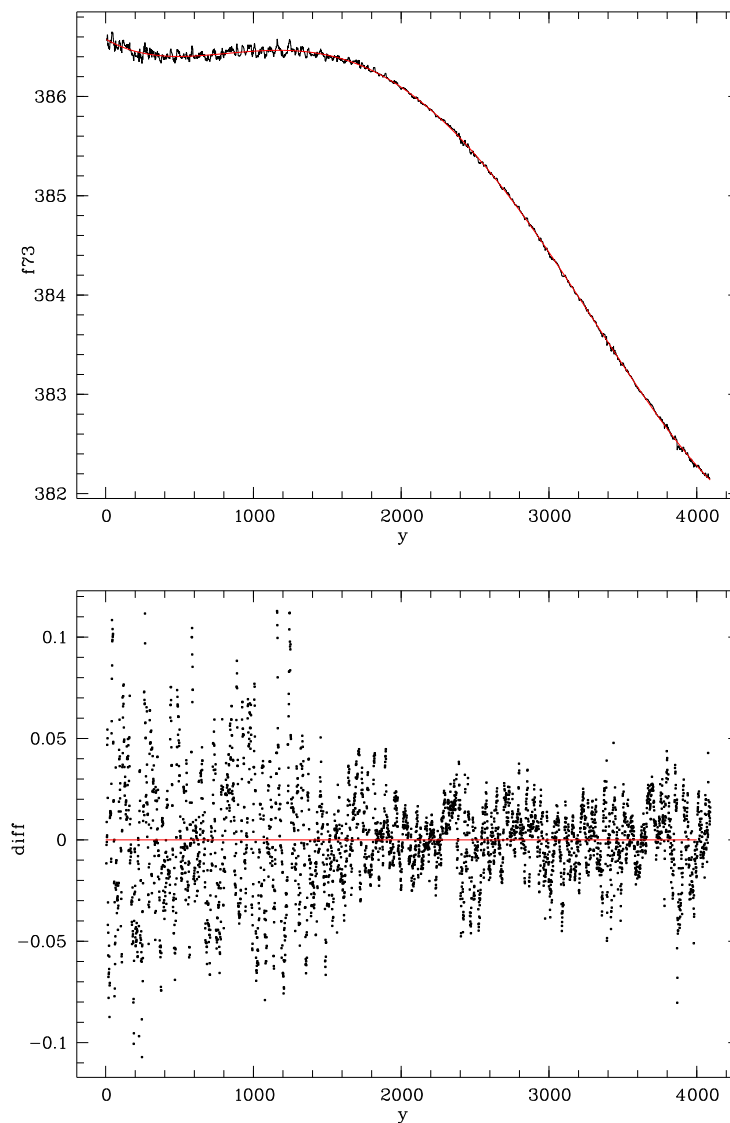


Figure 9.28.3: *Tracing of fiber spectrum 73 of HR\_orange flat field in quadrant 3. Both axis are in pixels.*

The list of  $X$  positions obtained for each fiber at each  $Y$  coordinate would then be modeled by a low degree

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polynomial, with the intent of eliminating the outliers and increasing the tracing accuracy. In the following this polynomial will be indicated with  $X_i(Y)$ , where  $i$  is the fiber sequence number.

During the spectral tracing operation, the presence of damaged or lost fibers will also be determined. If for a given fiber the search for a peak will fail beyond a given predefined rate, then the corresponding fiber will be flagged as “dead”, and will not be treated in the science spectra extraction.

The trace operation is carried out on a median filtered image of a flat field exposure (currently the smoothing box is set to 1x15 pixels), to avoid the derailment of the tracing by cosmic rays, bad pixels, or zero-order contamination in the case of LR observations. The accuracy of the tracing is typically of 0.01 pixel (see Figure 9.28.3).

The tracing of all the detected flat field spectra, performed by the recipe *vmifucalib* (see Section 7.19, page 120) leads to the definition of the extraction mask that will be used in the extraction of the scientific spectra associated to the flat field.

#### 9.28.4 Background subtraction

It can be seen that straylight is absent, or negligible, in VIMOS IFU scientific observations.

However, this is not the case for flat field exposures, where a straylight apparently correlated with the strong spectral signal can be observed. The background level is about 10% of the illumination level. This has no negative effect on the spectral tracing, but it may introduce a non-negligible bias in the determination of the relative transmission correction factors for each fiber.

If a complete tracing solution is available for a given exposure, it is possible to precisely locate the regions where the background level can be evaluated, *i.e.*, along the gaps between the 80-fibers blocks, and in any other portion not containing spectra. The background pixel values are fitted by a low degree bivariate polynomial, and this model values are interpolated and subtracted from the original image.<sup>21</sup>

#### 9.28.5 Determination of the fiber profiles

On a background subtracted flat field exposure, the first and the last spectra of each 80-fibers blocks are considered. The 10 half-profiles facing the background regions can be used to determine the fiber profile down to the zero signal level.

Preliminarily, following the accurate tracing of each fiber, the interpolated maximum value of the fiber signal at each coordinate along the dispersion direction is determined. Such values will be used in the normalisation of the pixel values obtained at each  $Y$  coordinate.

All the pixel values of the half profile are assigned to their distance from the profile centroid derived from the tracing solution (see Figure 9.28.4) up to a distance of 5 pixels where the ground level is reached.

Thanks to the spatial curvature, different pixelisations of the fiber profile are available at different positions along the dispersion direction. The fiber flat spectrum is cut into intervals each of the order of hundreds of pixels, and for each one of these intervals all the pixel values contributing to the profile are normalised to the value of the

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<sup>21</sup>This is not implemented in the current release.

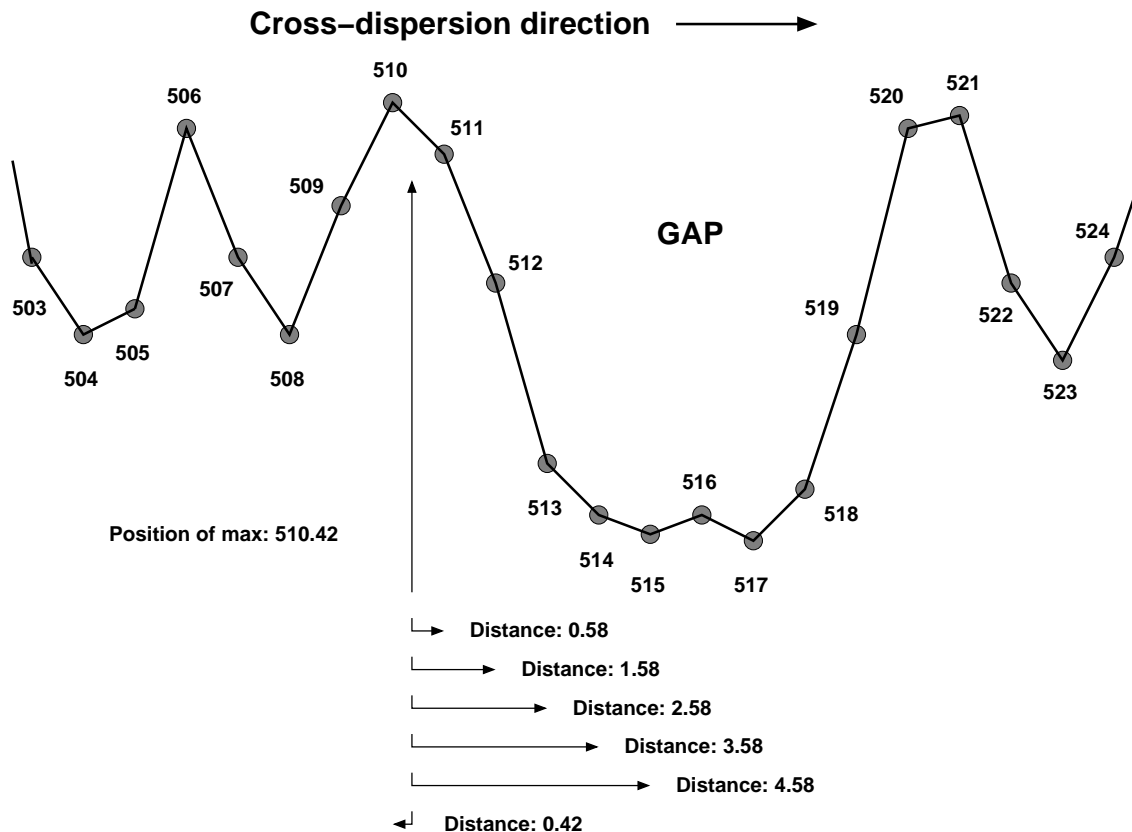


Figure 9.28.4: *Reading the fiber profile.* In this example, some fiber profiles around a gap between two fibers blocks are shown. The last fiber profile at the left of the gap peaks at the pixel position 510.42 (obtained from the tracing solution). The pixels distances from the peak position are assigned to each measured pixel value. Also, the value of the pixel immediately before the position of the maximum is used, since the contamination from the previous fiber is shown to be negligible (at about 1/3000 of the peak intensity).

peak maximum computed as described above. If the contributions from the 10 different fiber profiles are shown to be consistent with each other they may be merged into a single dataset.

In this way an interval of about 5 pixels is populated with direct evaluations of the empirical profile of the fiber spectrum. These values are then averaged within a grid of predefined bins, and tabulated.

Any change in the profile shape as a function of the chosen interval along the dispersion direction can also be modeled. Whether or not this will turn out to be necessary in the VIMOS IFU case will be decided as soon as a complete study of the reconstructed profiles is realised.

The colour dependency of the reconstructed profile is negligible (less than 2% between profiles reconstructed from red and blue regions), but the differences between the  $\sim 100$  studied fibers cannot always be neglected. In the current pipeline release the standard (numerical) model of the fiber spatial profile is adapted to the brightest (and uncontaminated) parts of the observed profile of each fiber. The fit is performed simultaneously in all wavelengths, in order not to introduce extra noise. This expedient significantly improves the spectral extraction, compensating for the differences between fibers, and managing the proper reduction of observations obtained in

less than optimal conditions (*e.g.*, out of focus).

Examples of reconstructed fiber profiles are given in Figures 9.28.5 and 9.28.6. Each plot contains about 24,000 pixel values covering the entire spectral range. The increase of noise in portions of the HR\_blue plot is due to pixel values coming from the faintest part ( $< 50e^-/\text{pixel}$ ) of the spectrum. Similar plots from LR grisms are perfectly consistent with the ones obtained from HR data, but contain less points. It should be noted that the slightest error in the tracing solution ( $> 0.05$  pixel) would introduce major discontinuities in plots like the ones in Figure 9.28.5.

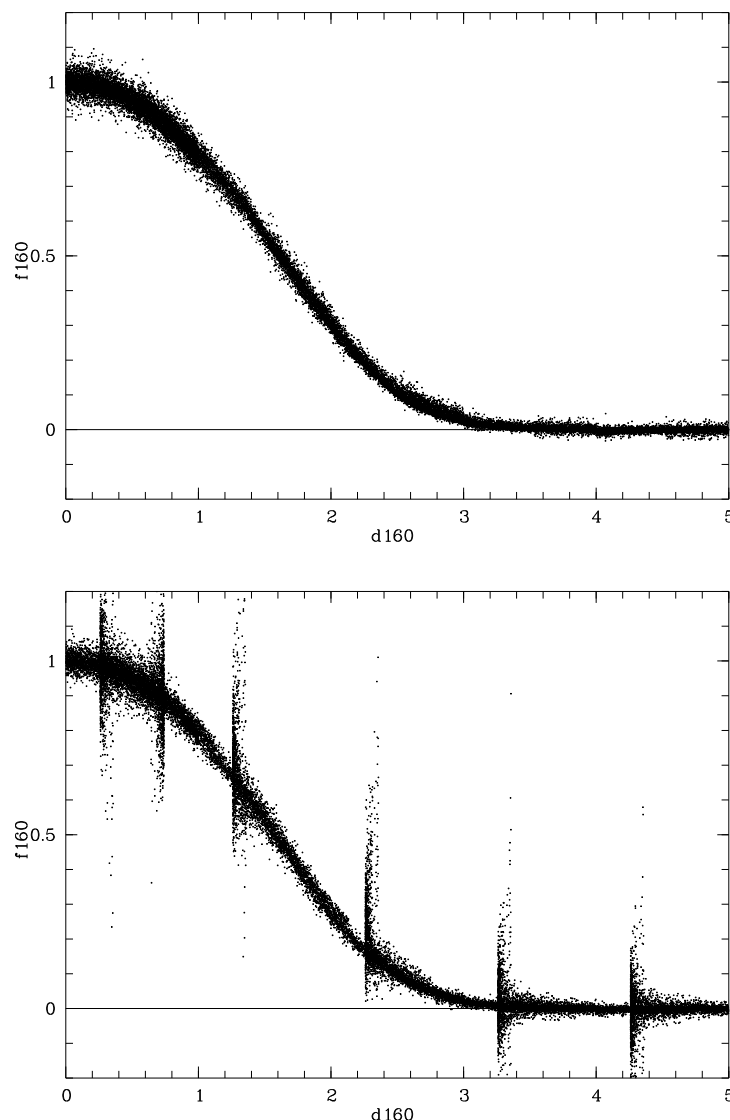


Figure 9.28.5: *Observed cross-dispersion profiles of spectra from fiber 160 on the central slit of quadrant 3.*

The modeled curve is the convolution of the true fiber profile with the pixel box. This is exactly what is needed in the spectral extraction process: any point of this curve is the value that a pixel at that distance from the profile

centroid would have. This makes the reconstruction of the profile to be used in the spectral extraction task at each pixel position along the dispersion direction trivial.

It should be noted that, if such a curve is reconstructed properly, the sum of all of its values sampled at a 1-pixel step should be approximately constant (for the curves in Figure 9.28.6 this constant is  $\sim 3.26$ ). For convenience, the fiber profile model may be normalised to make this constant equal to 1, that is:

$$\sum_i P(x_o + i) = 1$$

where  $P(x)$  is the normalised fiber profile having the maximum at  $x = 0$ ,  $x_o$  an arbitrary distance, and  $i$  any integer number between  $-\infty$  and  $+\infty$ . It can be shown that  $P(x)$  is not a gaussian, and it's not even the convolution of a gaussian with a box profile.

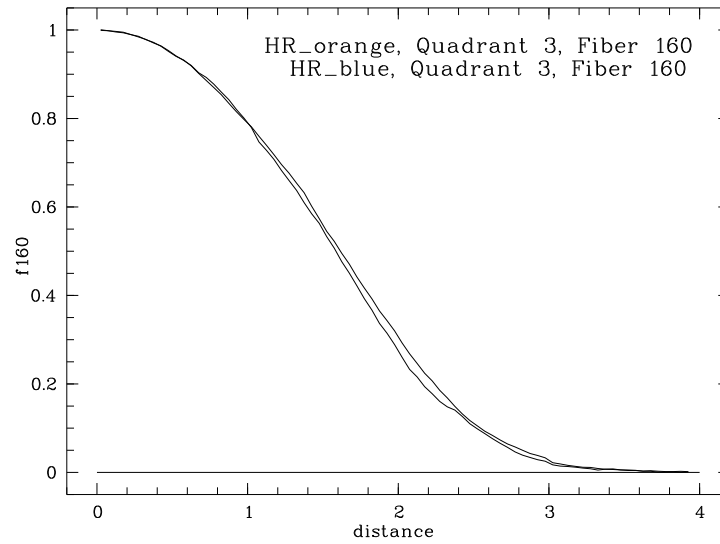


Figure 9.28.6: The smoothed profiles obtained from Figure 9.28.5 are compared. The fiber profile from the *HR\_blue* spectrum lays systematically below the fiber profile from the *HR\_orange* spectrum, but the difference is  $< 2\%$ .

In the current system, the same tabulated model profile is always used in the spectral extraction task (see Table 9.28.1). This profile was chosen as the median profile of a sample obtained from about 100 different fibers from the pseudo-slits of all quadrants.

Distance from centroid (pixel)	Profile intensity	Distance from centroid (pixel)	Profile intensity
0.025	1.00000	0.075	0.99996
0.125	0.99600	0.175	0.99363
0.225	0.99024	0.275	0.98371
0.325	0.97754	0.375	0.96946
0.425	0.95954	0.475	0.94931
0.525	0.93719	0.575	0.92335
0.625	0.90941	0.675	0.89560
0.725	0.87707	0.775	0.86130
0.825	0.84158	0.875	0.82178
0.925	0.80195	0.975	0.77927
1.025	0.76022	1.075	0.73276
1.125	0.70892	1.175	0.68236
1.225	0.65778	1.275	0.63209
1.325	0.60109	1.375	0.57527
1.425	0.54045	1.475	0.51107
1.525	0.48302	1.575	0.45345
1.625	0.42497	1.675	0.39587
1.725	0.36674	1.775	0.34252
1.825	0.31339	1.875	0.28750
1.925	0.26153	1.975	0.24057
2.025	0.21730	2.075	0.19604
2.125	0.17451	2.175	0.15626
2.225	0.13760	2.275	0.12041
2.325	0.10540	2.375	0.09260
2.425	0.07954	2.475	0.06847
2.525	0.05968	2.575	0.05272
2.625	0.04530	2.675	0.04062
2.725	0.03373	2.775	0.02871
2.825	0.02387	2.875	0.02167
2.925	0.01669	2.975	0.01503
3.025	0.01247	3.075	0.00993
3.125	0.00758	3.175	0.00669
3.225	0.00526	3.275	0.00301
3.325	0.00289	3.375	0.00123
3.425	0.00065		

Table 9.28.1: *Fiber profile model, normalised to its maximum intensity. A factor 3.0175 should be applied to the profile intensities to fulfill the relation  $\sum_i P(x_o + i) = 1$  (see text).*



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### 9.28.6 Aligning traces

In order to compensate for any difference introduced by instrument instabilities, the extraction mask, based on the fiber tracing  $X_i(Y)$  made on a flat field exposure, should be aligned to the tracings made on the science exposure.

The alignment is possible if at least one scientific spectrum is traceable. At long exposure times (more than about 30 minutes) the sky emission itself becomes traceable, while a short exposure on a completely dark field may rightfully be rejected as invalid. Only in the case of a short exposure on a pure emission line object no spectrum may be traceable, making an accurate data reduction impossible with this method.

The flat field tracing solutions are translated and rotated to a best match with the available science tracings. A single traced science spectra is sufficient to get alignment accuracies that are better than 0.1 pixels for all fibers. If however the instrument instabilities introduce signal displacements greater than 2 pixels, the scientific spectra will not be correctly identified, and the extraction mask alignment will be off by an integer number of fibers. The consequences might be disastrous, because the wrong tracings would be used to extract the scientific spectra, and the wrong relative transmission factors would be applied to them. In addition each scientific spectrum would be assigned to an offset position on the IFU head (see Figure 4.5.3, page 20), giving to the objects on the reconstructed field-of-view a typical zig-zagged appearance.

### 9.28.7 Spectral extraction

With a fiber profile model  $P(x)$  and the (aligned) trace  $X_i(Y)$  from each flat field fiber spectrum, it is now possible to extract all the scientific spectra. Let  $S(X, Y)$  be the value of a pixel of coordinates  $(X, Y)$  in the science frame, and  $F_i(Y)$  the (still unknown) total flux from the  $i$ -th fiber at the  $Y$  CCD coordinate.  $S(X, Y)$  will be the sum of all contributions from all the fibers to the pixel  $(X, Y)$  (cross-talk):

$$S(X, Y) = \sum_i F_i(Y) \cdot P(X - X_i(Y))$$

In practice, it is known that the contribution from fibers that are far from the  $(X, Y)$  position can be neglected. Taking into consideration just the 3 closest fibers to the  $(X, Y)$  pixel we may write

$$S(X, Y) = F_{j-1}(Y) \cdot P(X - X_{j-1}(Y)) + F_j(Y) \cdot P(X - X_j(Y)) + F_{j+1}(Y) \cdot P(X - X_{j+1}(Y))$$

where  $j$  is the number of the fiber having the minimum difference  $|X - X_i(Y)|$ . With 400 spectra laying along the cross-dispersion direction, and with each spectrum about 5 pixels wide, the above formulation is *for each*  $Y$  a redundant system of 2000 equations in the 400 unknowns  $F_i(Y)$ . This system should be resolved for each  $Y$  pixel value (*i.e.*, more than 3000 times).

With such figures, this may turn out to be a computationally heavy method for the determination of the spectra  $F_i(Y)$ . Moreover, even if this extraction method would completely eliminate the effects of the cross-talk between fibers, we could not consider this as an *optimal* extraction.

Formulas like Robertson's (Robertson, J.G., 1986, PASP, 98, 1220), that are meant to optimally extract mutually contaminating nearby spectra, redefine the optimal weights used in Horne's extraction (Horne, K., 1986, PASP, 98, 609) to the practical effect of entirely rejecting the spectral signal that turns out to be too contaminated by the other spectrum. In the IFU case, where the contamination is overall and systematic, this implies the loss of a lot of signal that could instead be recovered with the solution of the linear system shown above.

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At any rate, applying Robertson's formulation may turn out to be the only practically applicable choice. A first approximation of the spectral profile of the  $j$ -th fiber along the cross-dispersion direction must first be defined:

$$S_j(X, Y) = S(X, Y) - M_{j-1}(Y) \cdot \frac{P(X - X_{j-1}(Y))}{P(0)} - M_{j+1}(Y) \cdot \frac{P(X - X_{j+1}(Y))}{P(0)}$$

This approximation consists of subtracting from the observed profile  $S(X, Y)$  the contributions from the two nearby spectra, here modeled with the PSF rescaled to their observed peak values  $M_{j-1}(Y)$  and  $M_{j+1}(Y)$ . The following weights are defined:

$$W_j(X, Y) = \frac{S_j(X, Y)}{r^2 + gS(X, Y)} \cdot P(X - X_j(Y))$$

where  $r$  is the read-out-noise in electrons and  $g$  the gain factor in  $e^-/\text{ADU}$ . The optimally extracted spectrum (in electrons) would then be given by

$$F_j(Y) = g \sum_X W_j(X, Y) \cdot S_j(X, Y)$$

From the definition of the weights it is clear how abruptly they are set to zero as soon as the total signal  $S(X, Y)$  is not balanced by the estimate of the single fiber profile,  $S_j(X, Y)$ .

In the current implementation of the extraction task used by the IFU pipeline recipes, the spectral flux is estimated from the values of the 3 pixels closest to the centroid  $X_i(Y)$ , normalised by the tabulated fiber profile model (see Table 9.28.1, page 184), and then optimally averaged. It can be shown that, within a distance of 1.5 pixels, the cross-talk contamination between nearby fibers is always less than one part in a thousand (thanks to the arrangement of the fibers along the pseudo-slits, that never places fibers that are spatially far apart close to each other).

### 9.28.8 Wavelength calibration

The wavelength calibration is derived from an arc lamp exposure. The arc lamp spectra are extracted according to the procedure described in the previous section.

A rough optical distortion model would be initially used to unambiguously identify the brightest features of the extracted spectra. The search window for such features is wide, guaranteeing that even strong signal displacements would not prevent the identification of the reference lines. A rough wavelength calibration would then be used to search for the arc lines to be identified. In the particular case of LR observations, the expected positions of the zero order contamination on the CCD is determined, permitting to avoid regions that are too close to the zero order contamination. This search is required to return a number of lines at least twice the number of degrees of freedom of the fitting polynomial, and the model residuals should have an RMS always less than a specified threshold. If such requirements are not met, the whole result of the search is rejected, and the search is repeated anew, using wider and wider search windows - up to a certain limit. The first solutions found is then re-used as improved "first guesses", filling the gaps that are typically left behind after the first iteration.

The typical accuracy reached for the wavelength calibration is of about 0.2 pixels.

Once a wavelength  $\lambda$  is assigned to each Y pixel of each extracted spectrum, the positions of a number of predefined sky lines is determined on the extracted scientific spectra, and their median offset from their expected

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position is used to align the arc wavelength calibration to the scientific spectra. At this point the wavelength calibration is completed and the extracted scientific spectra are resampled in the wavelength space at a constant wavelength step.

### 9.28.9 Flat field correction

For IFU data, two alternative kinds of flat field correction can be considered:

*The “classical” flat field correction, i.e.,* dividing the bias subtracted raw data by a map of the fixed-pattern-noise of the CCD, before further reduction steps are applied to the data. The fixed-pattern-noise map may be obtained by averaging several IFU flat field exposures, and removing the large scale trends (including the fibers pattern). This is technically difficult to obtain with the necessary accuracy, and it has not yet been done.

*The extracted flat field correction, i.e.,* dividing the extracted scientific spectra by the extracted, normalised, transmission corrected, and large-scale-trend removed flat-lamp spectra. It should be noted that if this correction is applied, then the “classical” flat field correction (described at point 1) should not be applied. Moreover, dividing the extracted scientific spectra by the extracted flat-lamp spectra is just an approximate correction. The approximation is completely invalidated when we consider that the instrument flexures may have displaced the scientific spectra by a number of pixels with respect to the flat-lamp spectra. If the flat-lamp spectra were not extracted exactly from the same CCD regions as the scientific ones, the fixed-pattern noise would not be removed from the data, in fact it would be worsened.<sup>22</sup>

In the current system, no flat fielding correction is applied to the scientific data. The recipe *vmifucalib* (see Section 7.19, page 120) produces an image of extracted flat field spectra that may be used for an approximate flat fielding correction (using any interactive data reduction system, as MIDAS or IRAF).

### 9.28.10 Transmission correction

The spectral extraction procedure (see Section 9.28.7, page 185) is applied to the flat field exposure itself. Assuming that the flat lamp uniformly illuminates the IFU head, it is straightforward to obtain the relative transmission factors corresponding to each extracted spectrum.

The wavelength calibrated flat field spectra are integrated along a fixed wavelength interval, chosen where the spectra are brighter, and away from possible zero order contaminations from multiplexed spectra (in case of LR grism observations). The obtained integrals are normalised to their median value. The normalised values are what is currently used for the fiber-to-fiber relative transmission correction applied to the scientific spectra after their extraction. This is valid, under the assumption that the absorption law maintains the same shape for all fibers.

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<sup>22</sup>When a flat field correction is applied, a price is paid in terms of the increased variance of the processed signal, equal to the sum of the variances of the flat field and of the signal to be corrected; this price is only acceptable under the assumption that the removed fixed-pattern noise is greater than the noise added to the data by the flat fielding operation itself.

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### 9.28.11 Sky subtraction

Sky subtraction is probably the toughest problem in the VIMOS IFU data reduction process, because it will not be uncommon that the observed objects completely fill the IFU field. The only possibility is to select from all the reduced spectra the ones with the lowest signal, and classify them as sky spectra. Assuming that the transmission correction and the wavelength calibration had already been applied, their median spectrum would simply be subtracted from all the other extracted spectra. It is clear though that this way of proceeding is extremely risky. In the current implementation no sky subtraction is applied to the reduced data (with the exception of standard star spectra reduction, see recipe *vmifuscience*, Section 7.20, page 126).

### 9.29 vmifucalib

In this section the basic steps of the data reduction procedure applied by the recipe *vmifucalib* (see Section 7.19, page 120) are described. Please refer to Section 9.28, page 176, for more details about the basic operations.

The input flat field and arc lamp exposures are processed in the following way:

1. If more than one, the flat field exposures are combined with a specified stacking method, and the master bias is removed from the result. The master bias is removed also from the arc lamp exposure.
2. The flat field spectra are identified and traced as described in Section 9.28.3, page 179. This operation is performed for each illuminated IFU pseudo-slit (just one pseudo-slit in the case of HR and MR grism data, and four pseudo-slits in the case of LR grism data).
3. The obtained traces are fit with a 4th degree polynomial in the case of HR and MR grism data, or with a 3rd degree polynomial in the case of LR data. The accuracy reached is better than 0.04 pixels.
4. The tracing polynomial models are used to extract the flat field spectra and the arc lamp spectra. The extraction is based on the values of the three pixels that are closer to the trace of each fiber (see Section 9.28.7, page 185).
5. The wavelength calibration is obtained for each extracted arc lamp spectra (see Section 9.28.8, page 186). A 4th degree polynomial is used for relating wavelengths to CCD positions for HR and MR grism data, while a 3rd degree polynomial is used for LR grism data. The obtained accuracy is better than 0.3 pixels.
6. The extracted flat field spectra are resampled at a constant wavelength step (applying a flux conservation correction, and slightly oversampling the signal so that the wavelength step is a bit smaller than a CCD pixel), and used to determine the fiber-to-fiber relative transmission correction (see Section 9.28.10, page 187).

### 9.30 vmifuscience

In this section the basic steps of the data reduction procedure applied by the recipe *vmifuscience* (see Section 7.20, page 126, are described. Please refer to Section 9.28, page 176, for more details about the basic operations.

This recipe receives a science exposure, a master bias, and all the calibrations produced by the recipe *vmifucalib*, processing them in the following way:

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1. The master bias is removed from the science exposure.
2. The science exposure is analysed, in order to locate traceable spectra. This operation doesn't identify the detected spectra — it just determines their positions on the CCD.
3. If no traceable spectra are found, go to step 6.
4. The detected scientific spectra are traced, and the traces are modeled with a polynomial shape (see Section 9.28.3, page 179).
5. The extraction mask obtained from the flat field is aligned to the available tracing solutions on the science (see Section 9.28.6, page 185).
6. The science spectra are extracted along the (possibly modified) flat field tracings (see Section 9.28.7, page 185).
7. The wavelength calibrations for each fiber are used to determine the offset of a number of chosen sky lines from their expected positions on the CCD. The wavelength calibrations polynomials are corrected according to this offset. Currently, just the sky-lines at 5577.388, 6300.304, 6363.780, and 8344.602 Å are used.
8. The science spectra are resampled at a constant wavelength step (applying a flux conservation correction, and slightly oversampling the signal so that the wavelength step is a bit smaller than a CCD pixel).
9. The scientific spectra are divided by the relative transmission correction factors obtained with recipe *vmifucalib*.
10. The calibrated science spectra are integrated along a predefined wavelength range, chosen where the spectra are brighter, and away from possible zero order contaminations from multiplexed spectra. The obtained values are used in the reconstruction of the IFU field-of-view. The reconstructed field-of-view fills the region of an 80x80 image that corresponds to the reduced quadrant. In this way, the reconstructed image from 4 reduced quadrants can be easily obtained by the sum of the reconstructed images from different quadrants (see recipe *vmifucombine*, Section 7.22, page 130).
11. Flux calibration of extracted spectra (see Section 9.10).

### 9.31 vmifustandard

The data reduction steps applied by this recipe are the same as those applied by the *vmifuscience* recipe. The only extra operations are: an evaluation of the sky spectrum (see Section 9.28.11, page 188), and the determination of the total standard star spectrum from all the single fiber spectra. Finally, the efficiency and response curves are produced as described in section 9.9.

## A Abbreviations and acronyms

ADF	Aperture Definition File
ADM	Aperture Definition in mm
CPL	Common Pipeline Library
CRV	VIMOS spatial curvature model
DFS	Data Flow System
DO	Data Organiser
DRS	Data Reduction System
ESO–MIDAS	ESO's Munich Image Data Analysis System
FITS	Flexible Image Transport System
HR	High Resolution
ICS	Instrument Control Software
IDS	Inverse Dispersion Solution
IRAF	Image Reduction and Analysis Facility
IWS	Instrument WorkStation
LR	Low Resolution
MMU	Mask Manufacturing Unit
MOS	Multi Object Spectroscopy
MR	Medium Resolution
OPT	VIMOS optical distortion model
PAF	VLT PArAmeter File
PSO	Paranal Science Operations
PWS	Pipeline WorkStation
QC	Quality Control
SAO	Smithsonian Astrophysical Observatory
SDD	Software Development Division
SOF	Set Of Frames
TCS	Telescope Control Software
UT	Unit Telescope
VIMOS	VISible Multi-Object Spectrograph
VLT	Very Large Telescope
VMMPS	VIMOS Mask Preparation Software
WCS	World Coordinate System