FORS

Documentation of the Data Reduktion Software

Chapter MOS

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Contents

Chapter 2

Multi-Object Spectroscopy

Note

The default values for any parameters, input data, etc. are given in (**bold font**) *and keywords are marked by* $\boxed{\texttt{KEYWORD}}$.

2.1 Introduction

The MOS context is written for the reduction of multi-object spectra obtained with numerous slitlets. Long-slit spectra are considered a special case of multi-object spectra and therefore not treated in a separate chapter. The MOS package is meant especially for the reduction of FORS data but may also be used for other MOS data.
It is assumed that the basic correction for bias, dark, and overscan are performed with standard MIDAS commands (maybe also using `COMBINE/LONG` to average several frames of the same type). There are no special MOS averaging commands.
During the whole description we assume that the detector is a CCD with the rows along the dispersion direction and the columns along the slit.
A demonstration of the package can be obtained with the command `TUTORIAL/MOS`, which has an automatic and an interactive mode and also allows to look at selected parts of the package. In order to create all necessary test data you should run it once automatically.

2.2 Location of slitlets and flat-field correction

The very first step after correcting bias, dark, and overscan is to find the edges of the slitlets. This is done by the command `LOCATE/MOS`. This command locates the slitlets in an MOS flat-field frame by searching for the maximum (normalized) gradient in a trace perpendicular to the direction of dispersion. Position and width of the trace are given by $\boxed{\texttt{SCAN\_POS}}$ (**0,0**). $\boxed{\texttt{FLATLIM(1)}}$ (**0**) gives the minimum normalized gradient that must be exceeded, after median filtering the scan with a median of width $\boxed{\texttt{FLATLIM(2)}}$ (**0**) and discarding scan values below $\boxed{\texttt{FLATLIM(3)}}$ (**0**). The result is written to the output table $\boxed{\texttt{MOS}}$.tbl (which is used by most MOS commands) and the number of detected slitlets is written to $\boxed{\texttt{NSLIT}}$ (**0**). The programs allow at most 100 slitlets. If the algorithm does not find any slitlets the chosen threshold ($\boxed{\texttt{FLATLIM(1)}}$ (**0**)) may either be too high (above the intensity of the flats in the center of the frame) or too low (below bias value). Also the width ($\boxed{\texttt{FLATLIM(2)}}$ (**0**)) may be chosen to high or too small. Typical values are between 0.1 and 0.2 and 3 and 5, respectively.
It is also possible to define the slitlets interactively with `DEFINE/SLIT`. Here you first initialize the table $\boxed{\texttt{MOS}}$.tbl (**mos**) and then enter the limits with the cursor on the displayed flat field frame. This comand also allows an easy definition of the $\boxed{\texttt{MOS}}$ table for long-slit data.
With `LOCATE/MOS` the offsets in dispersion direction between the slitlets will be read from the header of the flat-field frame for FORS data and stored in the table $\boxed{\texttt{MOS}}$.tbl (**mos**) in column `:xoffset`. For other data or `DEFINE/SLIT` you will have to determine the offsets yourself using the command `OFFSET/MOS` on a wavelength calibration frame (see below).

As spectroscopic flat-fields normally exhibit the spectral characteristic of the lamp that was used to produce them you have to take out this characteristic in order to correct the CCD sensitivity variation and keep the original flux distribution. This is done with the command `NORM/MOS`. It takes an averaged flat frame and the slit limits stored in the table `MOS`.tbl. There are two methods provided for the normalization (`NORMMET` (**poly**)): In case `NORMMET=poly` it averages separately for each slitlet the rows, fits a polynomial of chosen degree (`FFORD` (**3**)) to the flux distribution obtained this way and divides each row in the slitlet by this polynomial. In case `NORMMET=median` it averages separately for each slitlet the rows, smooths with a median filter of `FFORD` pixels width and divides each row in the slitlet by the filtered average. You may also perform the flat correction at the same step using the command `FLAT/MOS`.

2.3 Wavelength Calibration

2.3.1 Detection of Arc lines

At first you have to find the calibration lines in the wavelength calibration frame belonging to your object. This is achieved by `SEARCH/MOS` which detects all lines separately for each slitlet and centers them either with center of gravity or with a gaussian fit. The search threshold and window are stored in `SEAPAR` (**200,5**). The positions of the lines, the CCD rows and the slitlets where the lines have been detected are stored in the table `LINPOS`.tbl (**linpos**). First the median of (`YBIN(2)` (**3**)) rows in the middle of each slitlet is calculated to search in this average spectrum for lines. Then in all rows the detected lines are centered using the line list obtained by the search algorithm. In this way we want to avoid unstable dispersion solutions which might arise from different line lists for different rows of the slitlet. In order to speed up the search you may decide not to take every row, but only some (`YBIN(1)` (**3**)) and for the detection of weak lines you may bin several row together (`YBIN(2)` (**3**)). In the case of the Gaussian centering method, blends could prevent the proper convergence of the non-linear fitting algorithm. The accuracy of the centering is significantly improved, if the peak flux of the Gaussian is hold fixed to be the meassured maximum value in the central pixel. Free parameters are σ and the center of the line.

2.3.2 Offsets between slitlets

If you have used `DEFINE/SLIT` there are no offsets copied to `MOS`.tbl automatically and you have to determine the offsets yourself using the command `OFFSET/MOS` on a wavelength calibration frame. This command will take the calibration spectra of the different slitlets and search for arc lines with the parameters given by `SEAPAR` (**200,5**). Correlating these line lists with that of the first slitlet gives the offsets relative to the first slitlet. The resulting offsets may be wrong if there are not enough or too many lines to get unambiguous correlation results. The safest way is to use this command after you are satisfied with the results of `SEARCH/MOS` **and** you have stored the parameters for threshold and width to `SEAPAR`. In this case you will **NOT** have **the offsets from the center of the CCD but relative to the position of the first slitlet!** The changing image scale over the detector can make the method unappropiate. Therefore it is strongly recommended to copy the offsets from descriptor data to the `MOS`.tbl table, but not from `OFFSET/MOS` – if possible.

Note

Before starting the calibration, a carefully selected line catalog must be prepared. Reject any line that is below the detection limit and any line which is blended!

2.3.3 Fitting the dispersion curve

Now you have several possibilities to perform your wavelength calibration. At first there are three different modes to identify the calibration lines (`WLCMET(1)` (**F**)):

Identify: You identify at least 2 arc lines in one slitlet with the command `IDENTIFY/MOS`. The command `CALIBRATE/MOS` then performs a first fit for the CCD row with the identified lines.

Linear: You know the central wavelength and the mean linear dispersion of your grism. These values are used as first fit of the first selected CCD row. You have to correct the value of this central wavelength if you used the command `OFFSET/MOS` to determine the offsets of your slitlets:

Example: Your reference slitlet has an offset of -100 relative to the center of the CCD in x-direction and you have a mean dispersion of 2 Å/pixel and a central wavelength of 5500 Å. This central wavelength will always lie at the x-position of the respective slitlet, which is in this case -100 pixels (i.e. -200 Å) from the center of the CCD. This means that you have a wavelength of 5700 Å at the center of the CCD within the reference slitlet. This wavelength should be used as `wcenter`, since the program assumes that `:xoffset = 0` means that the slitlet is at the center of the CCD in x-direction.

Recall: Method Linear is performed in the first slitlet. The dispersion coefficients of the this slitlet is recalled to calibrate the remaining slitlets. This identification is more stable in this case than for method Linear and the convergence of the fit is reached faster.

The first fit is used to identify as many lines as possible in the corresponding CCD row by comparing the fitted line positions to wavelength catalogue `LINECAT`.tbl (**hear**). For the identified lines a polynomial fit of chosen order is performed (using Legendre or Chebyshev polynomials - the type being selected with the keyword `POL_TYP` (**CHEBYSHEV**)). The line identification criterion will identify a computed wavelength (λ_c) with a catalog wavelength (λ_{cat}), if the residual

$$\delta\lambda = |\lambda_c - \lambda_{cat}|$$

is small compared to the distances to the next neighbours (in the arc spectrum as well as in the catalog):

$$\delta\lambda < min(\delta\lambda_c, \delta\lambda_{cat}) * \alpha$$

where $\delta\lambda_{cat}$ ($\delta\lambda_c$) is the distance to the next neighbour in the catalog (arc spectrum) and α is the tolerance parameter (0 ... 0.5) given by `ALPHA` (**0.2**). The automatic line identification is repeated with this polynomial fit in order to identify additional lines to further improve the dispersion curve.

Note

For very low dispersion spektroscopy one would expect that a linear guess will cause line mismatchs at the edge of the detector. One can avoid this, if more then two lines are identified with method Identify.

After the polynomial fit the residual of each line are checked and the line is thrown out, if it the residual exceeds the tolerance parameter `TOL` (**2**) (> 0 – in pixels; < 0 – in units of the wavelength). One of three fitting methods can be selected by keyword `WLCMET(2)` (**C**):

Constant fit in spatial direction: the dispersion coeficiants are constant for the whole slitlet. This method is typically appropriate for small slits.

Variable fit in spatial direction: bad lines are thrown out. Dispersion coeficiants are calculated for any row. The dispersion relation of the first fitted row is used as estimate for all following rows. A large number of arc-lines is required for this method. If there are only a few lines identified at the edge of the detector, small oscillations at the edge of the detector may occur in spatial direction.

Two dimensional fit over the slitlet: A two-dimensional fit is performed in spatial and dispersion direction over the slitlet. In spatial direction a "normal polynom" is fitted but a polynom as specified in keyword `POL_TYP` in dispersion direction. The dispersion coeficiants may smoothly evolve over the slitlet. This method is the most accurate for most applications, although the resulting residuals are typically larger than for a variable fit.

The iteration is repeated until a stable solution is obtained (and the minimum number of iterations `WLCNITER(1)` (**3**) is exceeded) or the maximum number of cycles (`WLCNITER(2)` (**20**)) is reached. The resulting dispersion

coefficients are stored in table `LINFIT`.tbl (**coerbr**), together with the r.m.s. error of the fit, the slitlet and the y-coordinates (world and pixel coordinates). Also a plot option for the resulting residuals (`PLOTC`, (**N**)) and various degrees of display (`DISP`, (**0**)) are available.
After fitting all rows of the respective slitlet with polynomials of the chosen order the program performs at last a linear fit to get the central wavelength and the mean linear dispersion necessary to derive a starting wavelength for the next slitlet from its known offset (modes Linear/Recall). In the mode Ident it tries to match the manually identified lines in the next slitlet, using the known offsets and a maximum allowed shifting tolerance stored in `SHIFTTOL` (**10**). Rows where no fit could be achieved are stored in the table `LINFIT`.tbl with the slit number -1.
Any selection of slitlets made in the table `LINPOS`.tbl will be taken into account, but all selections of the table `MOS`.tbl will be ignored. If you want those to be respected, too, redo the search for the wavelength calibration lines with the chosen selection in `MOS`.tbl.
After the wavelength calibration you may rebin your frame two-dimensionally to constant wavelength steps with `REBIN/MOS`. Point sources are normally wavelength calibrated after extraction (see below).

2.3.4 Automatic line identification and fitting of the dispersion curve

The automatic line identification is specially designed for focal reducers using grisms. From the location of the slit in the focal plane and the well known optical parameters of the grism and the instrument, it is possible to estimate the location of the spectral lines of the calibration lamp on the CCD. Although the automatic calibration can be done for other instruments, we will give in this section the parameters of FORS the focal reducer of the VLT as an example.
As the first step the spectral lines have to be detected with `SEARCH/MOS`. Then the calibration can be started with the command `CALIBRATE/GRISM`. The instrumental parameters like the tilt of the grism (7.5°), the focal length of the camera (280 mm) and the pixel size of the CCD detector (0.024 mm) are read from the command line. The parameters of the grisms are read from an input table. In columns `:idno`, `:gr` and `:phi` the identification numbers (eg. ESO identification numbers of the grisms), the number of grooves per millimeter and the prism angle are tabulated.

		grism parameters		
:idno	:name	:glass	:gr	:phi
12	GRIS_600B	FK5	600	34.0
14	GRIS_600R	K5	600	46.0
15	GRIS_600I	SF5	600	46.0
16	GRIS_600z	SF11	600	46.0
10	GRIS_300V	FK5	300	21.0
11	GRIS_300I	LF5	300	26.7
17	GRIS_150I	BaK2	150	11.5

Additionally the color dependence of the refractive index of the glass must be parametrised with the equation:

$$n^2 - 1 = \frac{n_0\lambda^2}{\lambda^2 - n_1} + \frac{n_2\lambda^2}{\lambda^2 - n_3} + \frac{n_4\lambda^2}{\lambda^2 - n_5} \tag{2.1}$$

The six parameters $n_0 \ldots n_5$ can be found in the Schott catalog "Optisches Glas" and must be tabulated in the table columns `:n0 ... :n5`.

		dispersion parameters of the glass					
:idno	:glass	:n0	:n1	:n2	:n3	:n4	:n5
12	FK5	8.443093e-01	4.751120e-03	3.441478e-01	1.498148e-02	9.107902e-01	9.786003e+01
14	K5	1.085118e+00	6.610995e-03	1.995620e-01	2.411087e-02	9.305117e-01	1.119828e+02
15	SF5	1.461419e+00	1.118261e-02	2.477130e-01	5.085947e-02	9.499958e-01	1.120419e+02
16	SF1	1.738484e+00	1.360686e-02	3.111690e-01	6.159605e-02	1.174909e+00	1.219227e+02
10	FK5	8.443093e-01	4.751120e-03	3.441478e-01	1.498148e-02	9.107902e-01	9.786003e+01
11	LF5	1.280356e+00	9.298544e-03	1.635060e-01	4.491358e-02	8.939301e-01	1.104937e+02
17	BaK	1.016622e+00	5.923838e-03	3.199031e-01	2.038284e-02	9.372330e-01	1.131184e+02

Finally the color dependence of the camera can be read from an input table, if the input table name is given as the seventh parameter. The table has to have columns with the names `lambda` and `fcam` which contain the wavelength in Å and the focal length in mm of the camera.

Like for command CALIBRATE/MOS the name of the line catalog is read from keyword `LINECAT` and the parameters for the line identification α from (`ALPHA` (**0.2**)), the rejection parameter (`TOL` (**2.0**)) and the polynom type `POL_TYP` (**CHEBYSHEV**)).

`CALIBRATE/GRISM` will first estimate the positions of the laboratory wavelength given in table `LINCAT` on the CCD and will then identify the closest spectral lines measured with `SEARCH/MOS` given in table `LINPOS`.tbl (**linpos**). The dispersion relation is fit by a polynom in both the spectral and spatial direction. Then the iteration is started rejecting first the lines which deviate more the `TOL` from the laboratory wave length and fitting later the dispersion curve from the remaining identification.

Note that the center of the optical beam is not necessarily identical with the center of the CCD and must be specified while starting the automatic line identification. If a descriptor `REFPIX` is given in the header of the input file `WLC` this value will be taken as the center of the optical axes. The entrance appature (long slit of mos slitlet) will not in the center of the field too. Therefore the offset to the center of field must be given in table `MOS` in column `:xoffset`.

To avoid oscillating solutions for the fit of the dispersion law, the coordinates are now transformed to the coordinate intervall $[-1,1]$. From now on the coeficients of the fit are not longer saved in table coerbr as table rows, but as file descriptors. A new function was coded to rebin the spectra later on, but all was coded compatible to older versions of CALIB/GRISM.

2.4 Definition of objects and sky subtraction

`DEFINE/MOS` helps you to localize your objects and sky regions and by default works automatically. It averages `XBIN` (**20**) columns around the position `SCAN_POS(1)` (**0 = center of frame**) (in world-coordinates!). In the target frame the program will detect objects above the threshold (`THRESH`, **-0.04**, see below) relative to the local background within the search window `WIND` (**5**) and fits a gaussian to the spatial profile of any detected object. The threshold may be given in absolute ($>$ 0.0) or relative ($<$ 0.0) numbers. It may be advisable to do at least a rough sky subtraction ahead of this command to facilitate the detection of the objects. In this case you have to use an absolute threshold for the detection of the object spectra afterwards. One may also think about rebinning the object frame to constant wavelength steps because then the search could be done in the same wavelength region for all slitlets. The limits of the objects are defined at the position where the gaussian fit has reached the detection limit `INT_LIM` (**0.001**). A safety margin of 3 pixels is taken on both sides of each object where no sky is automatically defined (can be overridden manually later) and the remaining part of the slitlets is taken as sky region. The results are stored in `WINDOWS`.tbl (**window**) and can be displayed in the overlay channel display and/or the graphics window. If you are not satisfied with the results you can change the windows interactively. You may also choose the interactive mode from the very beginning with `DEFWIN/MOS`. Then no automatic search is performed; instead you enter the the objects and sky regions for each slitlet by keyboard input. By default the sky region is defined as the complete slitlet.

The sky fit methods (`SKYMET`) available for `SKYFIT/MOS` are a simple median along CCD columns within each slitlet (`skymet=median`) and a more appropriate polynomial fit along the columns (`skymet=polynomial`), respectively. These two methods use only rows marked as sky regions in the table `WINDOWS`.tbl (**window**) to fit the sky background. With `skymet=nowindows`, however, the table `WINDOWS`.tbl is ignored and the sky is determined as a simple median over the full slitlet. The limits of the slitlets are taken in this case from `MOS`.tbl. This mode may be useful for a preliminary sky determination, before the object positions are known. If no sky regions are marked in some slitlet, the input frame is just copied to the sky frame for this slitlet. In this way, after sky subtraction, the slitlet contains only zeros thereby marking that the sky background is unknown for this slitlet. The keyword `SKYMET` contains the order of the polynom fit or the width of the median filtering, respectively. If a polynom fit is performed the cosmics must be rejected. `SKYFIT/MOS` rejects (but not replaces) pixels that exceed a given limit before the fit is performed. Read out noise, gain and the detection limit (in units of σ) must be given by keywords `SKYMET(1),SKYMET(2),REJTHRES`.

2.5 Extraction of objects

The object extraction `EXTRACT/MOS` is done with an optimum extraction scheme using different weights for the individual rows (following Horne, 1986, PASP 98, 609). With this command also the sky is subtracted. In addition the sky frame is needed to compute the optimum weights. The object postions are taken from the table `WINDOWS`.tbl. Cosmics are removed by assigning weight zero to the affected pixels. The procedure is iterative. If the number of iterations `EXTPAR(2)` is set to a negative number, a spectrum computed with equal weights is returned. The extracted spectra are stored in a 2-D frame, each line corresponding to one extracted object. In addition, the errors for the extracted spectra are returned, one line per spectrum, in the upper part of the same frame.
The command `REB1D/MOS` splits the 2-dimensional frame (produced by `EXTRACT/MOS`) up into 1-dimensional frames, one for each object. A root name is given and the rebinned frames are named by appending their row number to the root name. The extracted frames are rebinned to constant wavelength steps using the dispersion relation which has been obtained near the center row of the extracted objects.
If you prefer to avoid the resampling noise you can apply the dispersion relation to each pixel of an extracted frame (table option) without rebinning to constant wavelength steps with the command `APPLY/MOS`. This command produces for each extracted object a table with the columns `:FLUX, :FLUX_ERROR, :WAVELENGTH` and `:BIN`.

2.6 Data Structures

MIDAS tables and keywords are used to store most the information created and/or used by the MOS context. The tables `MOS`, `LINPOS`, `LINFIT`, and `WINDOWS` are created by the MOS commands; the table `LINECAT` is available in the **MIDAS** data base. A short description of the tables is given below; a detailed description of their contents can be found in Table 2.6.

`MOS`**.tbl** is created by `LOCATE/MOS` and used during the whole reduction process. It contains the limits of the slitlets.

`LINPOS`**.tbl** is created by `SEARCH/MOS` and updated by `CALIBRATE/MOS`. It contains the pixel-positions of the calibration lines, the row and the slitlet they belong to, their identifications and their intensities.

`LINFIT`**.tbl** is created by `CALIBRATE/MOS` and used by `REBIN/MOS`. It contains the fit coefficients for the dispersion relations of each row scanned by `SEARCH/MOS`.

`WINDOWS`**.tbl** is created by `DEFINE/MOS` and used by `FITSKY/MOS` and by `EXTRACT/MOS`. It contains the positions of the objects and the sky regions.

`LINECAT`**.tbl** contains the wavelength calibration lines. There will be several line-catalogs available in the instrument related system area, adapted for the use with the FORS grisms.

Context MOS	
APPLY/MOS	[EXTOBJEC] [LINFIT] [CALOBJEC]
CALIBRATE/MOS	[TOL] [WLCORD(1)] [WLCMET] [WCENTER,AVDISP] [PLOTC] [DISP]
DEFINE/MOS	[OBJ] [MOS] [WINDOWS] [THRESH] [WIND] [XBIN] [SCAN_POS(1)] [plotopt]
DEFINE/SLIT	mode [slit] [low,upp] [offset] [MOS]
DEFINE/WIND	[mode] [sequence] [obj] [sky] [MOS] [WINDOWS]
EXTRACT/MOS	[OBJ] [SKYFRAME] [WINDOWS] [EXTOBJEC] [EXTPAR] [CCDPAR] [REJTHRESH]
FLAT/MOS	[OBJ] [objf] [FLAT] [MOS] [NORMFLAT] [FFORD] [NORMMET]
HELP/MOS	[keyword]
IDENTIFY/MOS	[WLC] [YSTART] [LINPOS] [TOLWIND]
INIT/MOS	[session]
LINPLOT/MOS	[mode] [slit] [LINPOS]
LOCATE/MOS	[FLAT] [FLATLIM] [MOS] [SCAN_POS] [nml]
NORM/MOS	[FLAT] [MOS] [NORMFLAT] [FFORD] [NORMMET]
OFFSET/MOS	[MOS] [WLC] [SEAPAR]
PLOT/LOCATE	[MOS]
REBIN/MOS	in out [REBSTRT,REBEND,REBSTP] [REBMET] [LINFIT] [MOS] [WLCORD(2)]
REB1D/MOS	in root [REBSTRT,REBEND,REBSTP] [REBMET] [LINFIT]
RESPLO/MOS	[LINPOS] [ISLIT]
SAVE/MOS	[session]
SEARCH/MOS	[WLC] [SEAPAR] [YBIN] [CENTMET] [MOS] [LINPOS]
SHOW/MOS	[param]
SKYEX/MOS	[OBJ] [MOS] [WINDOWS] [LINFIT] [SKYPAR] [SKYMET] [EXTPAR]
SKYFIT/MOS	[OBJ] [MOS] [WINDOWS] [SKYFRAME] [SKYPAR] [SKYMET] [CCDPAR(1),CCDPAR(2),REJTHRES(1)]
FLAT/MOS	[OBJ] [objf] [FLAT] [MOS] [NORMFLAT] [FFORD] [NORMMET]
HELP/MOS	[keyword]
IDENTIFY/MOS	[WLC] [YSTART] [LINPOS] [TOLWIND]
INIT/MOS	[session]
LINPLOT/MOS	[mode] [slit] [LINPOS]
TUTORIAL/MOS	[mode] [action]
WLDEF/MOS	[WLC] [SEAPAR] [YBIN] [CENTMET] [TOL] [WLCORD(1)] [WLCMET] [PLOTC]

Table 2.1: Commands of the context MOS

Table MOS		
Label	**Unit**	**Description**
SLIT	–	sequential number of slitlet
YSTART	PIXEL	first row of slitlet
YEND	PIXEL	last row of slitlet
XOFFSET	PIXEL	offset of slitlet

Table 2.2: Table MOS

Table LINPOS		
Label	**Unit**	**Description**
X	PIXEL	x-position of calibration line
Y	–	world coordinate of row in which the line was found
PEAK	–	Peak intensity of calibration line
SLIT	–	number of slitlet in which the line was found
WAVE	Angstroem	identification of the line (Å)
WAVEC	Angstroem	fitted wavelength (Å)
RESIDUAL	Angstroem	WAVEC-IDENT (Å)
REJECT	–	Rejection code (-5: line has been rejected due to too large residual)

Table 2.3: Line positions table

Table LINECAT		
Label	**Unit**	**Description**
WAVE	ANGSTROEM	wavelength of calibration lines

Table 2.4: Line catalog table

Table LINFIT		
Label	**Unit**	**Description**
SLIT	–	number of slitlet in which the dispersion relation was determined
ROW	PIXEL	row in which the dispersion relation was determined
Y	–	world coordinate of ROW
RMS	Angstroem	r.m.s. error of dispersion relation (Å)
COEF_i	–	dispersion coefficients

Table 2.5: Line fit table

Table WINDOWS		
Label	**Unit**	**Description**
OBJ_SLIT	–	number of slitlet in which the object was found
OBJ_STRT	–	first row of the object's spectrum (world coordinates)
OBJ_END	–	last row of the object's spectrum (world coordinates)
NET_INTENS	–	net peak intensity the object's spectrum
SKY_STRT	–	first row of sky regions (world coordinates)
SKY_END	–	last row of sky regions (world coordinates)
SKY_SLIT	–	number of slitlet in which the sky was found

Table 2.6: Windows table

Table STANDARD		
Label	**Unit**	**Description**
MAGNITUDE	–	magnitude
WAVE	ANGSTROEM	wavelength
BIN	ANGSTROEM	bin width
FLUX	ERG/S/CM/CM/ANG	flux

Table 2.7: Standard star table

Name	Default value	Contents
Keywords for flat-field related commands		
FLATLIM/R/1/3	0,0,0	detection parameters for slitlet location (detection threshold, median width, lower limit)
FFORD/I/1/1	3	order of fit for the FF normalization
NORMMET/C/1/20	POLY	method for FF normalization
ISLIT/I/1/1	0	counter for slitlets
NSLIT/I/1/1	0	total number of slitlets
SCAN_POS/D/1/2	0,0	scan position and width for slitlet location
Keywords for wavelength calibration related commands		
SEAPAR/C/1/20	200,5	detection threshold and width
YBIN/C/1/20	3,3	Step and Binning in Y
CENTMET/C/1/16	GAUSS	centering method for calibration lines
XPOS/D/1/50	0.	Positions of identified lines (pixels)
LID/D/1/50	0.	Positions of identified lines (Angstroems)
WLCMET/C/1/2	FC	Wavelength calibration method (Ident/Linear/ Fors) and (Constant/Variable/Fit)
POLTYP/C/1/10	CHEBYSHEV	type of polynomials used for fitting (Polynom, Legendre or Chebyshev)
TOL/R/1/1	2.0	tolerance for autom. wavel. ident. (< 0 Å, $>$ pix)
TOLWIND/I/1/1	4	tolerance window for interact. wavel. ident.
WLCORD/I/1/1	2	order of fit used to compute the dispersion
ALPHA/R/1/1	0.2	Rejection parameter for lines matching [0,.5]
SHIFTTOL/I/1/1	10	tolerance for line identification from one slitlet to next
YSTART/I/1/1	0	Starting row for calibration (pixel value)
WLCNITER/I/1/2	3,20	Minimum, Maximum number of iterations
MAXDEV/R/1/1	10.	Maximum deviation (pixels)
WCENTER/D/1/1	0.	Central wavelength
AVDISP/R/1/1	0.	Average dispersion per pixel
PLOTC/C/1/1	N	Plot residuals of wavelength calibration
CAL/I/1/100	0	Results of moscalib (+1 dispersion relation fitted, -1 no dispersion relation fitted)
DISP/I/1/1	0.	amount of intermediate display for `CALIB/MOS`
GRISM/I/1/1 1	0	No. of grism used
REJTHRES/R/1/1	3.	rejection threshold

Table 2.8: Keywords used in context MOS

Name	Default value	Contents
Keywords for rebinning commands		
REBMET/C/1/12	LINEAR	Rebinning method (LINEAR, QUADRATIC, SPLINE)
REBSTRT/D/1/1	0.	Starting wavelength for rebinning
REBEND/D/1/1	0.	Final wavelength for rebinning
REBSTP/D/1/1	0.	Wavelength step for rebinning
Keywords for object extraction and sky subtraction related commands		
THRESH/R/1/1	-0.04	detection threshold for object search
WIND/I/1/1	5	detection window for object search
XBIN/I/1/1	20	Binning in X for object search
SCAN_POS/D/1/1	0.	center for scan (define/mos) in world coordinates
INT_LIM/D/1/1	0.001	fraction of central intensity where object limits shall be defined
NOBJ/I/1/1	0	number of objects found by define/mos
NSKY/I/1/1	0	number of sky-regions found by define/mos
SKYMET/C/1/16		method used to fit sky
SKYPAR/I/1/6	0	order of fit for polynomial or width of window for median
EXTPAR/C/1/80		extraction parameters (order, iter)
Keywords for frame names		
OBJ/C/1/60		object frame
EXTOBJEC/C/1/60		extracted object frame
CALOBJEC/C/1/40		extracted object frame
SKYFRAME/C/1/60	sky	sky frame
WLC/C/1/60	wlc	calibration frame
FLAT/C/1/60	flat	flat-field
NORMFLAT/C/1/60	normflat	normalized flat-field
Keywords for table names		
MOS/C/1/60	mos	table with slitlets' positions
LINFIT/C/1/60	coerbr	table with dispersion coefficients
LINPOS/C/1/60	linpos	table with wavelength positions
LINECAT/C/1/60	hear	table with wavelength positions
WINDOWS/C/1/60	windows	table with sky and objects positions

Table 2.9: Keywords used in context MOS (cont'd)

Name	Default value	Contents
Keywords for CCD parameters		
STEP/D/1/2	0.,0.	step-size of raw frame
START/D/1/2	0.,0.	start values of raw frame
NPIX/I/1/2	0,0	size of raw frame
CCDPAR/C/1/60		read-out-noise and conversion factor of CCD

Table 2.10: Keywords used in context MOS (cont'd)

2.7 MOS Cookbook - A typical session

2.7.1 Starting the whole thing

Before you start the MOS context you should have done the following preparations:

- average your bias frames
- average your dark frames
- average all flat-fields of the same setup
- correct the object frames for bias, overscan, and dark
- make sure that the dispersion direction in all your frames is along the x-axis

For the averaging of the frames you may want to use the command `COMBINE/LONG` from the context LONG. Now you can start the session with

Midas . . . > `SET/CONTEXT mos`

The initialization of the keywords to their default values is done by

Midas . . . > `INIT/MOS`

If you saved the results of an earlier reduction session with

Midas . . . > `SAVE/MOS session`

you can now initialize these parameters again (and restore all auxiliary tables) with

Midas . . . > `INIT/MOS session`

A demonstration of the package can now be obtained with

Midas . . . > `TUTORIAL/MOS`

which has an automatic (default) and an interactive mode (first parameter) and also allows to look at selected parts of the package (second parameter). In order to create all necessary test data you should run it once automatically.
Most of the numerical parameters are normally set to "sensible" values (which only means that they looked reasonable to the people who wrote this context), but the keyword for object ($\boxed{\texttt{OBJ}}$) is empty since there are no sensible defaults for these data. This holds also true for other keywords, which are normally filled either from the headers of your object (etc.) frames or with the results of MOS commands. Thus for the very first try you should just fill in the keyword mentioned above and continue (example see below).

Midas . . . > `SET/MOS obj=fors0001`

If you want to make sure that the setups of your files are all the same use the command `CHECK/MOS`.

!!! NOT YET IMPLEMENTED !!!

By default it will check the FORS keywords for

- slitlets' positions
- grism
- CCD parameters (e.g. binning)
- NAXIS, START, STEP

If your data were not produced by FORS you may give the FITS keywords that should be compared in an ASCII file. The use is then

Midas . . . > `CHECK/MOS file`

Now you may start the real business!

2.7.2 Locating slitlets and flat-field correction

The very first thing you should do now is to locate the limits of your slitlets because this information is needed for all further commands. Therefore you type

Midas . . . > `LOCATE/MOS`

This should produce the table `MOS`.tbl (**mos**) with the columns

`:SLIT`	sequential number of slitlet
`:YSTART`	first row of slitlet (world coordinates)
`:YEND`	last row of slitlet (world coordinates)
`:XOFFSET`	offset of slitlet from center of CCD

and write the total number of slitlets to `NSLIT` (**0**). It may be that the threshold defined by `FLATLIM)(1` (**0.15**) is either too low (e.g. below bias value) or too high for your data. Also, the width (`FLATLIM(2)`) (**4**) may be chosen to high or too small. If you detect too many slitlets, where only noise is visible, you should increase (`FLATLIM(3)` (**0**)). You also can change the scan position and width (`SCAN_POS`).
Then you should have a look at your flat-field and try again with

Midas . . . > `SET/MOS flatlim=threshold,width,limit`

Midas . . . > `SET/MOS scan_pos=xpos xbin=width`

Midas . . . > `LOCATE/MOS`

You may also try to identify the slitlets interactively with

Midas . . . > `LOAD {flat}`

Midas . . . > `DEFINE/SLIT init`

Midas . . . > `DEFINE/SLIT add ##`

where ## stands for the number of slitlets you want to identify. You will have to determine the offsets between the slitlets with `OFFSET/MOS` (see below).
If you do not have FORS data the column `:xoffset` will be set to zero. This is due to the fact that for FORS data the slitlet positions given in the header of the frame are transformed to offsets from the center of the CCD. This transformations is obviously not valid for other instruments. As you will need the offsets for the wavelength calibration frame you can determine the offsets **relative to the first one (which is not necessarily identical with the center of the CCD)** with

Midas . . . > `OFFSET/MOS`

As this command does a line search in the wavelength calibration frame `WLC`.bdf (**wlc**) and correlates only the detected arc lines the resulting offsets may be wrong if there are not enough lines to get unambiguous correlation results. Setting the parameter `SEAPAR` (**200,5**) to the values successfully used for SEARCH/MOS will help to yield reasonable results.
Normally spectroscopic flat fields show the spectral signature of the lamp with which they were taken. You can take out this spectral intensity distribution with

Midas . . . > `NORMALIZE/MOS`

By default this command will fit a polynomial of `FFORD`th (**3**rd) order to the averaged (along the slitlet) spectral intensity of the flat field (`FLAT` (**flat**)) (separately for each slitlet) and divide it by these fits. The results are stored in the frame `NORMFLAT` (**normflat**). Alternatively, you can normalize the flat field by dividing through an average smoothed with a median filter. To perform the actual flatfield correction together with the normalization type

Midas . . . > `FLAT/MOS`

This command will do the normalization and divide the frame `OBJ`.bdf by `NORMFLAT`.bdf. If you have not given any name for the result frame it will derive the name of the flat field corrected object frame by adding an 'F' to the name of the input frame (e.g. Ffors0001).

2.7.3 Wavelength calibration

Line search and interactive identification

The detection of arc lines in the wavelength calibration frame `WLC`.bdf (**wlc**) for all slitlets selected in `MOS`.tbl (**mos**) is done by

Midas ... > SEARCH/MOS

This command will take the slitlets' limits from `MOS`.tbl and the eventual stepping and binning factor from `YBIN` (**3,3**). In all CCD rows of `WLC`.bdf that are selected by these parameters it will look for intensities above the chosen threshold when comparing to the median intensity over a chosen window (threshold and window are defined by `SEAPAR` (**200,5**)). Any lines detected this way will be centered by `CENTMET` (**GRAVITY**) and stored in `LINPOS`.tbl (**linpos**).

:X	x-position of line (world coordinates)
:Y	y-position of line (world coordinates)
:PEAK	maximum intensity of line
:SLIT	number of slitlet

With

Midas ... > LINPLOT/MOS

you will get a plot of the x-positions of all found arc lines versus the CCD rows. With

Midas ... > LINPLOT/MOS 1 3

you will get a plot of the first CCD row of slitlet 3 for which line positions are stored in `LINPOS`.tbl. The detected lines are marked in the plot.
If you do not know the central wavelength and mean dispersion of the grism you used you have to identify at least two arc lines in any row of any slitlet.

Midas ... > IDENTIFY/MOS

The row, in which the lines shall be identified, is read from `YSTART` (**0**). If you do not provide any number either there or on the command line, the program will take the first CCD row that has been scanned. As frame it will use `WLC`.bdf.

Offsets between slitlets

To determine the offsets between the slitlets for Non-FORS data use

Midas ... > OFFSET/MOS

This command will take the calibration spectra of the different slitlets from `WLC`.bdf and correlate them with the arc spectrum of the first slitlet. Thereby it will derive their offsets relative to the first slitlet (**which will normally not be in the center of the CCD**).

Wavelength calibration

After identifying the arc lines you may now start the actual wavelength calibration with e.g.

Midas ... > SET/MOS wlcmet=IC

Midas ... > CALIBRATE/MOS

The first character of `WLCMET` gives the way the first lines are identified (**I**dentify, **L**inear, **F**ors), the second character gives the mode of fitting (**C**onstant or **V**ariable linelist, **F**it all). For a detailed description see subsection 2.3.3. This program fits a dispersion relation at first to the row with the identified lines, then to the slitlet, and afterwards to all slitlets (row by row, separately for each slitlet). The fitted line positions are compared to those listed in `LINECAT`.tbl (**hear**). The type of polynomials (Legendre or Chebyshev) is read from `POLTYP` (**CHEBYSHEV**), the fit order from `WLCORD(1)` (**1**), and the tolerance for automatic line identification from `TOL` ((**2**)). `TOL` can be given in pixel (> 0) or wavelength units (< 0). In case you know the central wavelength and the mean dispersion of the grism you used and you determined the offsets of the slitlets with `OFFSET/MOS` you have to correct the central wavelength for the offset between the center of the CCD and the reference slitlet used by `OFFSET/MOS`.

Example: Your reference slitlet has an offset of -100 relative to the center of the CCD in x-direction and you have a mean dispersion of 2 Å/pixel and a central wavelength of 5500 Å. This central wavelength will always lie at the x-position of the respective slitlet, which is in this case -100 pixels (i.e. -200 Å) from the center of the CCD. This means that you have a wavelength of 5700 Å at the center of the CCD within the reference slitlet. This wavelength should be used as `wcenter`, since the program assumes that `:xoffset = 0` means that the slitlet is at the center of the CCD in x-direction.

Then you can use the following command

Midas ... > `SET/MOS wcenter=central_wavelength`

Midas ... > `SET/MOS avdisp=mean_linear_dispersion`

Midas ... > `SET/MOS wlcmet=LC`

Midas ... > `CALIBRATE/MOS`

which will read the two parameters from `WCENTER` and `AVDISP`. If you have FORS data use

Midas ... > `SET/MOS wlcmet=RT`

Midas ... > `CALIBRATE/MOS`

This will read the grism number from the header of `WLC` and then take the parameters stored in the respective keyword. The plot option `PLOTC` (**N**) decides whether or not you get a plot of the residuals and the display option `DISP` (**0**) influences the amount of intermediate results displayed on screen. `CALIBRATE/MOS` stores the results in `LINFIT`.tbl (**coerbr**) in the columns

`:SLIT`	number of slitlet
`:ROW`	row for which dispersion relation was fitted (pixel coordinates)
`:Y`	row for which dispersion relation was fitted (world coordinates)
`:RMS`	r.m.s. error of fit
`:COEF_i`	fit coefficients

and adds to `LINPOS`.tbl (**linpos**) the columns

`:WAVE`	wavelength identification for :X
`:WAVEC`	fitted wavelength for :X
`:RESIDUAL`	:WAVE-:WAVEC
`:REJECT`	mark for rejected lines

Slitlets where no dispersion relation could be fitted are marked with '-1' in column `:SLIT`. With

Midas ... > `RESPLOT/MOS ? slit`

you can also get a plot of the residuals for a certain slit (`slit` = number) that are stored in `LINPOS`.tbl (**linpos**) (or in the first parameter given on the command line).

Automatic wavelength calibration for grism spectrographs

The automatic line identification and wave length calibration need an input table with the centers of the detected lines as a function of the y-ccordinate. Secondly it is required to calculate the absolute values of the x-offsets of the slitlets relative to the optical axes from the positions given in the frame's descriptors or the coordinates of the objects. `OFFSET/MOS` calculates only the offset relativ to the first slitlet in table `MOS`! The offset must be given in pixels not in world coordinates.
One can specify an input catalog with laboratory wavelength with the command:

Midas ... > `SET/MOS LINCAT=HeAr300`

Additionally the parameters `ALPHA` and `TOL` should be set to an appropiate value.

Midas ... > `SET/MOS ALPHA=0.2 TOL=1.0`

The program will be started the with the command:

Midas ... > `CALI/GRIS 0.5 5,4,3 12 7.5,280,0.024 1029 fors_grism.tbl`

Here the first parameter denotes the tolerance of the identification. If the line centers of the fit and the laboratory wavelength deviate by more then 0.5 wave length units the line will be rejected. The second parameter (5,4,3) specify the degree of the polynoms in x,y and the mixed term (x×y). Third the identification number (12) of the grism is given to select the table row with the grism table as given in parameter 6 (fors_grism.tbl). Then the tilt of the grisms (7.5), the focal length of the camera (280mm) and the pixel size of the detector (0.024mm) is given in parameter 4 and finally the center of the optics (1029) in pixels.
The output of the calibration is written to the table `coerbr`. The columns of table `coerbr` contain the dispersion coeficients given for the subsequent y-positions of the CCD. The output is written in the same way as with `CALIBRATE/MOS` to be consistent and to use the same commands (eg. for rebinning the data) for the further reduction steps.

Rebinning

You may now want to rebin your object frame to constant wavelength steps 2-dimensionally with `REBIN/MOS`. For this you have to provide start, end, and step of the wavelength range you want to rebin with

Midas ... > `SET/MOS rebstrt=start rebend=end rebstp=step`

and then use

Midas ... > `REBIN/MOS`

The interpolation between pixels along the x-axis is taken from `REBMET` (**LINEAR**) and the order of interpolation along the y-axis between scanned rows is read from `WLCORD(2)` (**1**).

2.7.4 Object definition and sky subtraction

To define your object's and sky regions use

Midas ... > `DEFINE/MOS`

By default it automatically averages `XBIN` (**20**) columns around the position `SCAN_POS` (**0=center of frame**) of the frame `OBJ` and searches for objects in this averaged frame that have an intensity above `THRESH` (**-0.04**) when compared to a median over `WIND` (**5**) pixels. `THRESH` can be absolute (> 0) or relative to the median intensity (< 0). It searches the slitlets that are defined by `MOS`.tbl (**mos**) and stores the results in `WINDOWS`.tbl (**window**). The plot option (**0**) defines whether you get a two-dimensional display of the result, a graphical plot, both, or nothing (default).
If an object is detected a gaussian is fitted to its spatial profile and the limits of the object's region are defined at those pixels where the gaussian fit has reached `INT_LIM` (**0.001**) of the central intensity. On both sides of each object a safety margin of 3 pixels is established (can be overridden manually later); the remaining slitlet is defined as sky region. It may be advisable to perform a very crude sky subtraction first to get rid of

the sky continuum intensity. This can be done with `SKYFIT/MOS` with `skymet=nowindows`. This command determines the median value along the columns over the slitlets. If you choose this way you should use an absolute threshold for object detection. If you want to search for all objects at the same wavelength region you have to rebin your frame first to constant wavelength steps with `REBIN/MOS`.
After the automatic definition of objects' and sky regions you are asked if you are satisfied with the results. If you are not (or are not yet sure), you answer 'no' and can now inspect the results more closely in the graphical plot and also change the results manually. You may also start with the interactive definition using `DEFWIN/MOS`. The results are stored in table `WINDOWS` (**windows**):

`:Obj_Slit`	number of slitlet for object
`:Obj_Strt`	first row of object
`:Obj_End`	last row of object
`:Sky_Slit`	number of slitlet for sky
`:Sky_Strt`	first row of sky
`:Sky_End`	last row of sky

The command `SKYFIT/MOS` is used to fit the sky. Normally, the sky regions are taken from the table `WINDOWS`.tbl. Several sky windows may be defined in each slitlets. To fit the sky background you may use the median along the sky regions (`skymet=median`) or a polynomial fit (`skymet=polynomial`). Method polynomial requires rejection of cosmic rays and bad pixels. These pixels are rejected by `SKYFIT/MOS` before fitting the data. Read out noise (in electrons), gain (electrons/adu) and the rejection criterion in units of σ must be specified in keywords `CCDPAR` and `REJTHRES` (**3**).

Midas . . . > `SKYFIT/MOS ? ?  ?  ?  3 poly 8,2.3,3`

does a polynomial fit of 3^{rd} order in the frame `OBJ`.bdf, in the regions defined by `WINDOWS`.tbl (within the slitlet limits listed in `MOS.tbl`) and stores the result in `SKYFRAME` (**sky**).bdf.

2.7.5 Object extraction

Use `EXTRACT/MOS` to sky-subtract and extract the detected objects in an output frame with an optimum extraction scheme using different weights for the individual rows (following Horne, 1986, PASP 98, 609). The procedure is iterative. If the number of iterations `EXTPAR(2)` is set to a negative number, a spectrum computed with equal weights is returned. The sky frame (`SKYFRAME` (**sky**)) and the CCD read-out-noise and gain (`CCDPAR`) are used to compute the errors of the resulting spectra. The extracted spectra are stored in a 2-D frame, each line corresponding to one extracted object. In addition, the errors for the extracted spectra are stored in this frame, one line per spectrum.
To rebin the resulting frames to constant wavelength steps use:

Midas . . . > `SET/MOS extobjec=in`

Midas . . . > `SET/MOS rebstrt=start rebend=end rebstp=step`

Midas . . . > `REB1D/MOS ? reb`

This will split the extracted frame in.bdf into individual frames with constant wavelength steps, named reb0001, reb0002, etc. using the dispersion coefficients of `LINFIT`.tbl.
If you want to avoid rebinning noise you can use `APPLY/MOS` to produce a table with the columns `:WAVELENGTH, :FLUX, :FLUX_ERROR,` and `:BIN`.

Midas . . . > `SET/MOS extobjec=in calobjec=ap`

Midas . . . > `APPLY/MOS`

This will take the frame in.bdf and convert it to tables ap0001.tbl, ap0002.tbl, etc. using the dispersion coefficients of `LINFIT`.tbl.