FORS

Documentation of the
Data Reduktion Software

FORS 2 in Echelle mode

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Contents

Chapter 5

Data reduction of Echelle spectra

5.1 Introduction

The following code was developed for the automatic data reduction of Echelle spectra to be taken with FORS 2. All programs except of the crude guess of the order positions and the wavelength can be also used for spectrographs with a different design but the first guess is only applicable for focal reducers using two grisms. It has been tested with data taken with DFOSC in Echelle mode.
Some concepts are very different in comparison to the exisiting Midas Echelle package and the FEROS package. To find the orders and the arc lines from the calibration lamps a guess of the order positions and the wave length is done, calculating the positions from the parameters of the instrument optics and the grisms. With this concept we avoid any problems with blended lines, because only the isolated lines (of the eg. HgCrHeNeAr lamp) are centered at the forecasted positions.
In contrary to the Echelle package and the FEROS package we keep all spatial information along the slit and provide programs the rectify the curved orders to normalize the flat fields along the slit and to subtract the night sky lines along the slit.
Like the FEROS package a routine is provided to do an optimum extraction of faint and small sources. Like for FEROS the extraction is done on the un-rebinned frames and cosmics can be removed iteratively. To merge the spectra and to calculate the response function for the later flux calibration, routines from context Echelle can be used.
To extend this code for spectrographs like CASPEC is possible. A program is required which can write the position of the orders in columns :x and :y, the order number in column :order and the forecasted wavelength in column :lambda. It is certainly not very difficult to calculate this input table for a spectrograph using gratings.
To avoid conflicts with the pipeline reduction no global keywords and fits descriptors are used to store the parameters, but all is written to the table generated by the first routine `GUESS/EF`. To be consistent with the Echelle context some fits header keywords were written to the rebinned frames.

5.2 Problems to be eliminated

This is demo version of the package! Some problems are known to the authors and will be rejected in time.

coordinate systems: For FORS 2 it is planed the the coordinate system is such that the center of the optical path is coordinate 0,0 on pixel numbers approximately 1033,1019 with start values below zero. This shouldn't be a problem, but has not been tested yet.

Two MOS slits in the focal plane If there are two MOS slilets in the focal plane one has to start the programs twice with different slit boundaries. It has not been checked if this will cause problems.

More then one targets in the slit and/or two MOS slits in the beam: The extraction of spectra and the determination of the sky background considers only one target in the slit.

Online HELP Online help files doesn't exist yet.

5.3 GUESS/EF – the guess of the order position and the wave length

The program GUESS/EF calculates the xy-postion for given wavelengths and order number. Input parameters are the focal length of the camera, the pixel size, the grism parameters like the prism angle the density of the grooves and the tilt of the grism. The refractive index of the grism is calulated for all input wavelengths. Finally the xy-position of the slit must be given and the center of the optical path.

From the input parameters the positions of the selected orders is calculated and written to an input table which will be used for the later reduction steps. The following parameters are required for the program:

parameter	default	type	description
P1	orders	T	output table
P2	brdf0022	I	reference image
P3	9,10,7,19	N	two grism numbers,1st and last order
P4	6,6,0.015	N	tilt_ech,tilt_xdisp,pixel_size
P5	1026,1026,1026,17,-266	N	Center of optical path on CCD (x,y)
P6	dfosc_grism.tbl	T	Grism table
P7	dfosc_xgrism.tbl	T	Grism table cross dispersers
P8	dfosc_fcamera.tbl	T	table with focal length of the camera

Parameter P3 contains the grism ID numbers of the Echelle (9) and the cross disperser (10) and the number of the first and last order to be reduced. Parmeter P4 contains the tilt of the grisms and the pixel size of the DFOSC CCD. Parameter P5 contains the position of the center of the optical path in pixels. The third number is a dummy and the last numbers are the offset of the slit position in respect to the center of the focal path. The last three parameters contain the table names for the grism parameters and the cromatic dependence of the focal length of the camera:

grism parameters - Echelle				
:idno	:name	:glass	:gr	:phi
9	DFOSC_ECH	LF5	79	65.8
grism parameters - cross dispersers				
:idno	:name	:glass	:gr	:phi
10	DFOSC_XD	UBK7	160	6.283

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

$$n^2 - 1 = \frac{n_0\lambda^2}{\lambda^2 - n_1} + \frac{n_2\lambda^2}{\lambda^2 - n_3} + \frac{n_4\lambda^2}{\lambda^2 - n_5} \tag{5.1}$$

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`.

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.

The prgram will generate the following columns of table "orders.tbl":

	column name	unit	format
TLABL001:	order	order	I4
TLABL002:	lambda	Angstroem	F8.2
TLABL003:	X_pos	mm	F8.2
TLABL004:	X	pxl	F8.2
TLABL005:	Y_pos	mm	F8.2
TLABL006:	Y	pxl	F8.2

5.4 `DEFINE/EF` - the centering of the order positions

After the guess the forecasted positions are read from the input table and the postion of the order is accurately determined with a Gaussian centering algorithm in y-direction. The centered position are than taken as the input of a polynom fit of the y-position a a function of x for all orders to be reduced.
Te followin input parameters must be given to the program:

parameter	default	type	description
P1	orders	T	output table
P2	brdf0022	I	reference image
P3	3,4,20	N	degree of polynom, x-window, y-window
P4	1026,1026,1026,17,-266	N	Center of optical path on CCD (x,y)
P5	7,1.4,3	N	ccd parameters RON,gain,kappa
P6	0.6	N	threshold for bad order positions in pixels

For P1 the table generated by `GUESS/EF` must be given as well as P2, the input frame to be used for the centering of the order position. P3 is the degree of the polynom for the fit of the order, x-window the radius in x within the columns are averaged and y-window the radius with we expect to find the order. P4 was descibed for `GUESS/EF`. P5 are the read out noise, the gain and the factor of sigma to specify the minimum level of flux at which the centering will be done. P6 is the threshold in pixels at which the obtained positions are rejected in the second iteration.
At the present time the routine was tested with a bright object as the order reference, but it is more accurate to use a pinhole in the center of the focal path as the refererence. The other routines will allow to extract slits and spectra with an y-offset in respect to this position. Two columns are created in the input/output table "orders": `:YC` the meassured center of the order and `:YCC` the fitted center of the order after the polynom fit and the rejection of bad meassurements. Additionally the coeficients of the polynom fits are stored in columns `:coeforder7 ...:coeforder19 for the given example` and the numerical parameters, such as the order of the polynom the number of orders and the order numbers (7. . . 19) are stored in column `:orders`.

5.5 `CALIBRATE/EF` - centering of the spectral lines and wavelength calibration

From the guess of the order and wavelength positions we can estimate the crude positions of the tabulated arc lines from the catalog and it is possible to select the unblended lines to be centered in the first iteration. A line is selected if the next line is more the a given radius in pixels of the position of the line. For the next iterations the radius can be significantly reduced, but it should be much larger the the line width to ensure a good centering. Then the global dispersion function is calculated with a non-linear two-dimensional χ^2 - optimization. The wave length depend on `:X` and `:order`. For the first iterations only the positions in the center of the slit are meassured and taken into account. After the usefull lines have been found in the center of the slit, the parameter matrix of the 2D-optimization is hold constant, and the arc-lines are centered along the slit in spatial direction (Δy) and the dispersion is fit in dependence of x, order and Δy. Only the components of the 3D-parameter tensor, which depend on Δy are variable, while all other parameters are hold at the optimum value of the 2D-problem.

The parameter of the program are:

parameter	default	type	description
P1	orders	T	input table
P2	rdf0023	I	input frame
P3	5,5,-10,10	N	y-window,dystep,dystart,dyend
P4	1026,1026,1026,17,-266	N	Center of optical path on CCD (x,y)
P5	thar25.tbl	T	input table with laboratory wavelength
P6	7,1.4,3	N	ccd parameters RON,gain,kappa
P7	20,5,12	N	x-window-guess, iterations, x-window-center
P8	1	N	tolerance in Å

The first two parameters are the input table with the order position and the guess of the wavelength and the input frame with the wavelength calibration exposure. P3 is the number of pixels in y to be avaraged for the centering, the step size in y the start value in dy and the end value in dy units for the centering, where the slit starts and end relative to the order reference position. P4 is the center of the optical path and the position of the slit respectively, as explained earlier on. P5 is the input catalog with the loboratory wavelengths of the calibration lamps. P6 are the CCD parameters which are used to calculate the weigths for the χ^2 optimization for the gaussian centering and as threshold for the detection of lines. Lines below 3σ (in the example) are rejected. P7 are the windows for the centering. The first number is the radius of the initial line search and centering. The second number is the number of "iterations", but not only the bad lines are rejected but the window size for the centering is reduced by 1 pixel after any iteration. The third number the window size of the second iteration. P8 is the threshold within which the lines are considered for the fit given in wavelength units. The program will create two temporary tables lines{P1}.tbl which contains the position of the lines in the center of the slit for any order to be reduced and lines{P1}_3D.tbl which contains the centers of the selected lines along the slit in spatial direction. The parameter matrix of the global solution for the center of the slit is stored in column `:coef_2D` and the parameter tensor of the calibration along the slitlets is stored in column `:coef_3D` of the input/output table (orders.tbl in the example). The input table with the laboratory wavelength shoul be well selected appropiate to the subsequent spectral resolution. It should include all lines detectable although some of these lines are blended!

5.6 `NORMALIZE/EF` - normalization of the flat field

For the later reduction step like the determination of the sky background and the optimum extraction, is is necessary to calculate the normalized flat field. The flux in the center of the slit is calculated within a given radius Δy in y-direction. Then the calulated spectrum of the halogen lamps is smoothed calculating the median of the given radius in x-direction. Later the 2D-spectrum of the halogen lamp is divided by the smoothed 1D-spectrum of the halogen lamp along the spatial direction.

Input parameters are:

parameter	default	type	description
P1	orders	T	input table
P2	brdf0039	I	input frame
P3	50,-15,15	N	iradx,idystart,idyend
P4	1026,1026,1026,17,-266	N	Center of optical path on CCD (x,y)

The first two parameters are the input table with the order positions and the crude flat field frame. The third parameter P3 is the radius of the median to be calculated and the start and end value of the slit relative to the reference order position in pixels. P4 is the location of the center of the optical path and the position of the slit relative to the optical path.

The program will calculate three output frames: the rectified normalized flat field {P2}_recitfied.bdf the normalized flat field {P2}_normalized.bdf and the smoothed spectrum of the halogen lamps {P2}_blaze.bdf which contains a crude information of the blaze function for a preliminary normalization of the Echelle orders.

5.7 SKYFIT/EF - determination of the sky background

The sky background is calculated in spatial direction on the unrebinned frames. The frames must be divided by the normalized flat field before. The sky can be calculated on unrebinned frames in the case of FORS, because the slit is approximately in the center of the optical path and the curvature of the the night sky lines due to the non-linear distortion due to the grism is expected to be small. Alternatively the median method and the polynom fit method can be applied. For the median method the median is calculated within a wind of a given size for any pixel. For the polynom method the bad pixels and cosmics are eliminated iteratively.
The input paramters of the code are:

parameter	default	type	description
P1	orders	T	input table
P2	nbrdf0022	I	input frame
P3	1026,1026,1026,17,-266	N	Center of optical path on CCD (x,y)
P4	7,1.4,5	N	ccd parameters RON,gain,kappa
P5	MEDIAN	?	method
P6	9	N	sky parameter: window size / order of polynom
P7	-15,15,-4,4	N	idystart,idyend, lower, upper

The first two parameters are the input table and the flat fielded science image. P3 is the center of the optical path and the position of the slit on the CCD relative to the center of the optical path. The fourth parameter P4 are the CCD parameters and the clipping factor for the rejection of bad pixels and cosmics in the case of method polynom. P5 is the method with which the sky is determined: MEDIAN or POLYNOM. P6 is the radius of the median or the order of the fit for the subsequent methods. Finally P7 denotes the boundary of the slit to be fit and the upper and lower limit were the target is located on the slit. The order of the polynom should be selected as small as possible for method polynom, while the median radius should be as large as possible but smaller then the typical scale of the curvature of the terrestric lines for method median.
The program will create an image {P2}_sky.bdf with the estmated background from the night sky.

5.8 RECTIFY/EF - rectification of the curved spectra for spatially resolved objects

The program reads the fit parameters for the position of the orders and calculates the y-position of the orders for any x-pixel of any order. It does a linear rebinning in y and writes the rectified spectra to the disk.
The input parameters are:

parameter	default	type	description
P1	orders	?	input table
P2	brdf0039	?	input frame
P3	-15,15	?	idystart,idyend
P4	1026,1026,1026,17,-266	?	Center of optical path on CCD (x,y)

The first two parameters are again the input table and the raw frame. The 3rd and 4th parameters are the slit boundaries and the position of the center of the optical path and the slit, respectively. The name of the output frame will be {P2}_rectified.bdf

5.9 `REBIN/EF` - rebinning of spatially resolved objects

The rectified spectra can be rebinned with `REBIN/EF` to equal wavelength steps. The program reads the dispersion coeficients of the 3D-χ^2 fit and calculates the wavelength for any pixel as a function of x, order and Δ y and writes the data to a master frame which containes all orders and output frames for any single order to be merged later on. To be consistent with Midas context Echelle the start wavelength and the number of extracted pixels of the extracted slits is stored in descriptors `WSTART` and `NPTOT` of the rebinned master frame, for the later attempts to merge the spectra after the flux calibration.
Input parameter of the routine are:

parameter	default	type	description
P1	orders	T	input table
P2	snbrdf0022	I	input frame
P3	-15,15	N	idystart,idyend
P4	1026,1026,1026,17,-266	N	Center of optical path on CCD (x,y)
P5	0.5	N	step size

Again the first two parameters are input table and input frame to be rebinned, and the third and fourth parameters the length of the slit to be extracted and the position of the center of the path and the slit respectively. As the fifth parameter the step size of the rebinned image must be given in wavelength units.
Output frame {P2}_rebinned.bdf will be created as the master frame which contains all orders in one frame, and frames {P2}_o7.bdf ... {P2}_o19.bdf with extracted slit of the the single orders.

5.10 `EXTRACT/EF` - optimum extraction of spectra

The routine `EXTRACT/EF` extracts a spectrum of a point source or a very small source from the curved raw spectrum, which must be divided by the normalized spectrum before to allow the modelling of the spatial profile and the masking of the cosmics.
In the first iteration the order position is calculated and all pixels are re-sampled to groups with same sub-pixel offsets relative to the fitted order position. For the sub-samples the spatial profiles are estimated with a polynom fit and finally the estimated profiles are used to mask cosmics and the weigth the pixels dependent on the flux level in an optimum way.
High signal to noise data should not be treated in the same way because the systematic deviation due to the sampling is expected to be larger then the photon noise, while the optimum extraction will reject pixel with a flux level above a given threshold in units of the photon noise. Optionally the program can therefore extract bright sources with equal weight and without rejetion of the cosmics.
Input parameters are:

parameter	default	type	description
P1	orders	T	input table
P2	nbrdf0022	I	input frame
P3	1026,1026,1026,17,-266	N	Center of optical path on CCD (x,y)
P4	7,1.4,5	N	ccd parameters RON,gain,kappa
P5	4,4,5	N	extraction parameter order,niter,sample
P6	-13,13,-7,7	N	idystart,idyend, lower, upper

The first parameters are the input table and the root name of the raw but flat fielded science spectrum. It is expected that a file {P2}_sky.bdf exists which contains the result of the sky calculation if program `SKYFIT/EF`. The 3rd parameter consist again of the position of the optical path and the slit in pixel units. 4th parameter is the read out noise and gain of the CCD and the clipping factor for the rejection of cosmics. It is recommended not to set this parameter too small, if the flux level is high as the pixels with high flux will be rejected in this case. If the number of iterations is set to a number below 0 an equal weight spectrum will be extracted. The

fifth parameter consists of the order of the fit for the spatial profiles and the number of iterations for the profile fit the masking of cosmics along the profile as well of the number of samples to be treated seperately. If 5 is given like above the pixels which are sampled between 0 and 0.2 are sorted to sample 1 and between 0.2 and 0.4 to sample 2. Finally the boundaries of the slit and the boundary limits within which the spectrum of the target will be extracted are given.
The program will create two 1D-spectra {P2}_extract.bdf and {P2}_stdev.bdf which contain the extracted spectrum and the "deviation of the model profile from the real data" which is here defined as the square root of the χ^2 for the optimum extraction and the photon noise expected for the flux level of sky and science frame in the case of a normal equal weight extraction.

5.11 `REB1D/EF` - rebinning of extracted spectra

The program is used to rebin the extracted spectra from `EXTRACT/EF`. It reads the 3D-dispersion coeficients and calculates the wavelength of any pixel of the extracted spectra. to calculate the offset relative to the center of the slit the extraction parameters as used for the extraction must be given as a parameter. At the present time only linear rebinning is supported.
Input parameters are:

parameter	default	type	description
P1	orders	T	input table
P2	nbrdf0022_extract	I	input frame
P3	-13,13,-7,7	N	idystart,idyend, lower, upper
P4	1026,1026,1026,17,-266	N	Center of optical path on CCD (x,y)
P5	0.5	N	step size

The first two parameters are the input table and the name of the extracted spectrum, the 3rd parameter P3 are the extration boundaries as specified for `EXTRACT/EF`. The boundaries of the slit are not used by the program but the location of the target. P4 are the center of optical path and the slit and P5 is the step size in wavelength units.
An output master file {P2}_rebined.bdf is created which containes all orders rebined. In the header of the master file the descriptors `WSTART` and `NPTOT` are stored, which allows the use of the programs `MERGE/ECHELLE` and `RESPONSE/ECHELLE` from the Midas Echelle package.

5.12 `RESPONSE/EF` - calculation of the instrument response

The program calculates the response function from the observed flux of the standard star and the tabulated flux from the literature. It expects the flux given in units of $10^{-16}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,Å^{-1}}$. The atmospheric extinction is taken into account.
Input parameters are:

parameter	default	type	description
P1	?	I	input frame
P2	?	T	input table: calibrated flux
P3	?	N	air mass,gain(e/adu),mirror_size(cm)
P4	50	N	smooth window in pixel
P5	{P1,O_TIME(7)}	N	exposure time in seconds
P6	atmoexan	T	input table: atmospheric extinction
P7	:LA_SILLA	TC	column with atmospheric extinction

The first two parameters are the image with the raw flux in adu and the input table with the expected flux of the standard star in units of $10^{-16}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,Å^{-1}}$. The third parameter is the air mass, the gain factor in e/adu

and the size of the telescope aperture in cm. The forth parameter is the window of the median to smooth the response function and the fifth parameter is the exposure time in seconds. The last two parameters are the input table with the tabulated atmospheric extinction and the column of the subsequent table with the values of the atmospheric extinction in units of magnitude per air mass.
The program will create two output images {P1}_response.bdf and {P1}_photons.bdf with the calibration factors in units of $e^{-}\ s^{-1}\ Å^{-1}$ / $erg\ s^{-1}\ cm^{-2}\ Å^{-1}$ and adu / photons respectively.

5.13 `FLUXCALI/EF` - flux calibration of extracted slits

The extracted slit are flux-calibrated by the command `FLUXCALI/EF` using the instrument response function obtained with `RESPONSE/EF`. The atmospheric extinction is considered by the program.
Input parameters are:

parameter	default	type	description
P1	?	I	input frame
P2	?	I	image with spectral response
P3	?	N	air mass,gain(e/adu)
P4	{P1,O_TIME(7)}	N	exposure time in seconds
P5	-15,15	N	idystart,idyend
P6	atmoexan	T	input table: atmospheric extinction
P7	:LA_SILLA	TC	column with atmospheric extinction

The first parameter is the raw extracted input spectrum rebined to the same wavelength steps. The second parameter is the response function obtained by program `RESPONSE/EF`. The third parameter is the air mass and the gain factor in e/adu. The forth parameter is the exposure time in seconds. For the fifth parameter the values of the slit boundaries have to be the same as for the extraction of the slit. The lower and upper boundary of the slit have to be given in pixels relative to the position of the order reference. The last two parameters are the input table with the tabulated atmospheric extinction and the column of the subsequent table with the values of the atmospheric extinction in units of magnitude per airmass. The resulting flux is given in units of $erg\ s^{-1}\ cm^{-2}\ Å^{-1}$ per pixel. One output file {P1}_flux.bdf with the calibrated spatially resolved spectrum is created by the program.

5.14 `FLUX1D/EF` - flux calibration of extracted spectra

The response function calculated with `RESPONSE/EF` is taken to compute the absolute flux from the raw extracted and rebined spectrum. The atmospheric extinction is considered by the program.
Input parameters are:

parameter	default	type	description
P1	?	I	input frame
P2	?	I	image with spectral response
P3	?	N	air mass,gain(e/adu)
P4	{P1,O_TIME(7)}	N	exposure time in seconds
P5	atmoexan	T	input table: atmospheric extinction
P6	:LA_SILLA	TC	column with atmospheric extinction

The first parameter is the raw extracted input spectrum rebined to the same wavelength steps. The second parameter is the response function obtained by program `RESPONSE/EF`. The third parameter is the air mass and the gain factor in e/adu. The forth parameter is the exposure time in seconds. The last two parameters are the input table with the tabulated atmospheric extinction and the column of the subsequent table with the values of the atmospheric extinction in units of magnitude per airmass. One output file {P1}_flux.bdf with the calibrated extracted spectrum is created by the program.

5.15 MERGSLIT/EF - merging the extracted slit

The flux-calibrated and rebinned orders can be merged with MERGSLIT/EF. The flux of the subsequent orders is weightened with an image containing the standard deviation for an optimized mergeing of the orders. The standard deviation must be calculated in advance. The rectified image before the sky was subtracted must be rebinned - the standard deviation if the square root of this frame, but the minimum value shoud be greater then the read out noise. The resulting frame with the standard deviation must be flux calibrated like the input frame with the flux. Alternatively a dummy image containing value 1 in all pixels can be given to the code for an equal weight mergeing.

Input parameters are summarized in the table below:

parameter	default	type	description
P1	?	?	input frame - flux
P2	?	?	input frame - stdev
P3	20,20	N	wavelength interval to be skipped: start,end
P4	-15,15	N	idystart,idyend

The first two frames are the rectified, rebined and flux calibrated input images with the flux and the standard deviation. The third parameter allows to specify how much of the spetrum will be clipped at the edge of the orders at the blue and the red edge respectively. It has to be given in wavelength units. The last parameters is the slit boundary in respect to the order reference. Two output frames will be created: the merged spectrum {P1}_merged.bdf and the merged standard deviation {P2}_merged.bdf.

5.16 MERG1D/EF - merging the extracted spectra

The extracted spectra can be merged with MERG1D/EF. Again an optimum merging is done, if realistic values for the standard deviation are given. The program is the same as MERGSLIT/EF, but the forth parameter is not required here.

Input parameters are summarized in the table below:

parameter	default	type	description
P1	?	?	input frame - flux
P2	?	?	input frame - stdev
P3	20,20	N	wavelength interval to be skipped: start,end

The first two frames are the extracted, rebined and flux calibrated input images with the flux and the standard deviation. The third parameter allows to specify how much of the spetrum will be clipped at the edge of the orders for the blue and the red part of the order respectively. It has to be given in wavelength units. Again two output frames will be created: the merged spectrum {P1}_merged.bdf and the merged standard deviation {P2}_merged.bdf.