

ESO Phase 3 Data Release Description

Data Collection	FORS2-SPEC
Data Provider	ESO, Science Data Quality Group
Document Date	27 February 2024
Document Version	1.0.2
Document Author	Danuta Dobrzycka, Sabine Möhler, Wolfgang Hummel, Burkhard Wolff

Abstract

This is the release of reduced spectra from the FORS2¹ - the visual and near-UV Focal Reducer and low dispersion Spectrograph 2 for the Very Large Telescope (VLT) of the European Southern Observatory (ESO). Data of the three spectroscopic modes of FORS2 are included in this release: long-slit spectroscopy (LSS) using a mask with 6.8' long slits of different widths, and multi-object spectroscopy with movable slit blades (MOS, slit length about 20") or with masks (MXU, arbitrary slit length). The spectra are taken using a wide variety of gratings with different wavelength ranges and dispersions. They include a set of normal gratings, which cover the full operational wavelength range of FORS2 with essentially three different dispersions (230 Å/mm, 110 Å/mm, and 45 to 50 Å/mm) and medium resolution, high throughput holographic gratings, which are based on volume-phased holographic gratings cemented between two glass prisms. The response of the holographic gratings depends on the position on the CCD along the dispersion axis. This requires specific steps during the flux calibration, which are handled correctly by the pipeline. The gratings can be combined with filters for order separation or more specialized settings.

This release is an open stream release. It is complete from beginning of the year 2015 until present. The data content is not fixed but grows with time as new data are being acquired and processed (approximately with monthly cadence and with a delay of one to two months).

The data have been reduced using the FORS2 pipeline version 5.6.1 or higher. Processing includes flat fielding, wavelength calibration, correction of spatial distortion, sky subtraction, optimal extraction of spectra, and flux calibration (not considered to be absolute flux calibration).

The processing is performed at ESO in an automated process. The pipeline processing uses the archived, closest-in-time, quality-controlled, and certified master calibrations. The reduction process is largely automatic. There is an automatic scoring process for the quality control, review and certification of the data products, and information is provided to the users (see the "QC flag" description below) regarding the non-zero scores.

The FORS2 pipeline extracts spectra from a single exposure. If several exposures on the same target are executed within the same observing template then an additional

¹ <http://www.eso.org/sci/facilities/paranal/instruments/fors2.html>

reduction step is performed for this release. The extracted and flux-calibrated spectra of the single exposures are stacked into a co-added spectrum with increased signal-to-noise ratio. The combined spectrum becomes the primary product; the single spectra are made available as associated files. For the co-adding step, the ESOTK pipeline is used (version 0.9.5 or higher).

Disclaimer. Data have been pipeline-processed with the best available calibration data. However, please note that the adopted reduction strategy may not be optimal for the original scientific purpose of the observations, nor for the scientific goal of the archive user.

Release Content

The FORS2-SPEC release is a stream release. The content of the release grows with time as new data are being acquired and processed. The data are tagged "FORS2-SPEC" in the [ESO archive user interface](#).² The release contains data from instrument modes Long-Slit Spectroscopy (LSS), Multi-object spectroscopy with the Mask exchange Unit (MXU), and Multi-Object Spectroscopy with movable slitlets (MOS).

Occasionally, the standard mosaic of two red sensitive, 2k×4k MIT CCD detectors is replaced with a mosaic of two blue-sensitive 2k×4k E2V CCDs. This release includes only data taken with the MIT CCD detectors.

First data have been published in October 2022 and they covered observations obtained since January 1st, 2022. Within time, also the historical science observations were produced based on the re-processed calibration products. Currently, the release contains observations since January 1st, 2015. Please note that the files follow the standard ESO data access policy. The products inherit access rights of the raw parent files, which means that they become public after the proprietary period (typically one year after the observations) has expired.

Data Selection

Data selection is based on the following keyword values:

- Instrument: INSTRUME = FORS2
- Category: HIERARCH ESO DPR CATG = SCIENCE
- Type: HIERARCH ESO DPR TYPE = SKY
- Instrument mode: HIERARCH ESO INS MODE = LSS, or MXU, or MOS.

In processing of the FORS2 science data, no selection is made on the basis of the observing mode (visitor or service). Data with ‘test programme IDs’ starting with ‘60’ or ‘060’ are not processed.

Settings. Data in all spectroscopic modes taken with different grisms or grism+order-sorting-filter combination are processed (if the necessary master calibrations exist), with the following exceptions:

- Long-slit data using wide slits (HIERARCH ESO INS SLIT WIDTH > 1.06 nm, corresponding to HIERARCH ESO INS SLIT WID > 2 arcsec) observations

² http://archive.eso.org/wdb/wdb/adp/phase3_spectral/form

- Any spectra using filters other than the order separating filters GG375, GG435, or OG590
- MOS and MXU observations taken with grism GRIS_150I without order sorting filter, as there are no good calibrations for this setup (see description below)

The products have the keywords OBSTECH=SPECTRUM (long-slit spectroscopy), MOS (multi-object spectroscopy with movable slitlets), and MXU (multi-object spectroscopy with masks) in the ESO archive user interface.³

Data sets and input files. Processing of FORS2 spectroscopic science data is based on single exposures. Every science exposure is pipeline-processed and results usually in several extracted, flux-calibrated 1-dimensional spectra (because the pipeline extracts all spectra it detects) and a few additional products. Among those a first selection is performed:

- Spectra with S/N < 2 are discarded as they may correspond to spurious sources
- Spectra with a ratio of the saturated pixels, in the region from which the spectrum was extracted, to all pixels in that region > 0.03 are discarded
- Spectra with ratio of the zero-flux background pixels > 0.5 (or max-background and min-background < 0.001) are discarded, as they may correspond to spurious sources
- Spectra with value of the keywords: QC TRACE CURVATURE, DRS LAMRMS, and NAXIS2 exceeding set thresholds are discarded, as they indicate problems with the calibrations used for processing

Often a science observation consists of several exposures on the same object executed within the same template (same value of HIERARCH ESO TPL START), using the same guide star). In such a case extracted spectra fulfilling the additional requirements listed below are co-added into a combined spectrum.

The selection criteria are:

- Difference of calculated on-sky position < 0.5 arcsec with respect to the first spectrum
- S/N within a factor of 5 of the first spectrum

This step is performed independently of the original intent of the observation, i.e. whether the intention was to add the exposures in order to get a higher signal-to-noise ratio or to study a time series. In any case, individual single-exposure spectra are available as associated files in addition to the combined spectrum. Observations from different template executions (possibly using different guide stars) on the same target are not combined.

Release Notes

Pipeline Description

A detailed description of the FORS2 pipeline can be found in the pipeline user manual which is available from the ESO pipeline web page⁴. The initially released data set

³ http://archive.eso.org/wdb/wdb/adp/phase3_spectral/form

⁴ https://www.eso.org/sci/software/pipelines/index.html#pipelines_table

was processed with version 5.6.1 of the pipeline. The actual version used for processing can be found in the header of any product in the keyword PROCESOFT.

Combination of spectra from single exposures is done with the `esotk_spectrum1d_combine` recipe. A detailed description is available from the ESO pipeline web page. The initially released data were processed using version 0.9.5 of the ESOTK pipeline.

Data Reduction and Calibration

Reduction steps. Data reduction includes bias subtraction, flat fielding with normalized flat fields, wavelength calibration and distortion correction, extraction of 1-dimensional spectra with sky subtraction and flux calibration. To extract the spectra, objects are searched and extracted from all the 2-dimensional slit spectra. More than one object can be inside the slit and produce spectra. The pipeline extracts anything that can be detected in the wavelength-collapsed calibrated 2-dimensional frame. This may sometimes lead to spurious detections and the extraction of spectra with very low S/N, consistent with residual sky. This is the reason for the removal of spectra with $S/N < 2$ from the stream.

Flat field and wavelength calibrations. For FORS2 spectroscopic modes flat field and wavelength calibration is performed in one processing step. Flat field and arc lamp frames are used together to trace the slits and determine the spatial distortion correction. Therefore, they are acquired within the same template to ensure that the mask position does not change between the exposures. Flats and arc lamp frames are taken using an internal screen. For the wavelength calibration the He, HgCd, and Ar lamps are used (at the lowest spectral resolution with grism GRIS_150I) and in addition the Ne lamp (at higher resolution). The calibrations are observed during daytime only, with the telescope pointing to zenith and the instrument in calibration position.

Static calibration data. In addition to calibration frames taken regularly, the FORS2 pipeline also uses static calibration tables like e.g. collection of reference wavelengths for the arc lamps and grisms used, or grism tables containing grism-specific parameters. The static calibrations used in processing the science data are listed in Table 1.

Sky subtraction. For all spectroscopic modes, LSS, MOS and MXU, the median sky subtraction model is used (option *skymedian*). It consists of subtracting a median value of the sky for each wavelength pixel of each rectified slit spectrum in the 2D frame before source extraction. This is the most robust sky subtraction method in case of crowded fields or extended objects, while, at the same time, not harming observations of the sparse fields. Please see the [Known Features and Issues](#) section for description of known problems with the sky subtraction that can affect the FORS2 spectroscopic data.

Spectrum extraction. To extract the spectra, objects are searched and extracted from all the slits. The pipeline does not select the spectra to be extracted based on header information but instead extracts anything that can be detected in the wavelength-

collapsed calibrated 2-dimensional frame. This may result in several extracted spectra per slit, including spurious spectra with very low S/N, consistent with sky residual.

Flux calibration. Both extracted 1-dimensional spectra and rectified 2-dimensional spectra are flux calibrated using the master response curves (`PRO.CATG = MASTER_SPECPHOT_TABLE`), that were carefully derived for most grisms and grism+order_separation_filter combination using wide-slit observations of spectrophotometric standard stars. There are no master response curves for the rarely used settings GRIS_1200g, GRIS_600V+GG435, GRIS_600R+GG435, GRIS_600I+OG590, and GRIS_200I+OG590. For those setting, the response curves derived from the closest in time spectrophotometric standard star observations are used.

Combination of spectra. For the combination of spectra, the generic recipe `esotk_spectrum1d_combine` is used. For the combination, data are combined using an error-weighted mean (`--collapse.method=WEIGHTED_MEAN`) and the information in the QUAL column (`--use-quality-column=TRUE`).

Calibrations used for data reduction. Table 1 lists the required calibration types that are needed for the reduction of science data. Please see the pipeline user manual for further details.

Table 1 FORS2 spectroscopy calibrations

Type	Purpose
Bias	Measures the residual, fixed pattern of the detector bias.
Flat field and wavelength calibrations	Removes pixel-to-pixel variations, provides wavelength calibration and spatial distortion correction.
Grism table	Provides grism-specific parameters like the dispersion in A/pixel, the start and end wavelength, the polynomial degree to be used for the wavelength calibration, fit parameters for the response curve, etc.
Global distortion table	Provides correction of the spatial distortion for long-slit spectroscopy. It exists for most, but not all grisms and is an optional input.
Extinction table	Describes the atmospheric extinction at the Paranal Observatory.
Response curve	Corrects the shape of the spectra for variations of detector sensitivity and grism and filter throughput

All calibrations used in this release have been processed with pipeline version 5.5.7, 5.6.1, or higher. Effort is made to ensure that calibration and science data for FORS2 are processed with the same or consistent pipeline versions.

Products

The primary FORS2 science data product is a 1D spectrum. The file has one table extension. It is the result of either a single exposure or a combination (“stacking”) of spectra resulting from individual exposures. The table columns contain the wavelength (WAVE), the extracted flux (FLUX) and its error (ERR), the uncalibrated sky background (BGFLUX), the uncalibrated flux (FLUX_REDUCED), its error (ERR_REDUCED), and a quality column (QUAL) flagging wavelength regions that should be ignored (for instance due to missing coverage by the master response curve).

There are several additional files which are associated to the primary product:

- 1) The PNG plot files that visualize the primary product and provide quality control (QC) information
- 2) All extracted spectra from the individual exposures if the primary product is a co-added spectrum; then, also the PNG files corresponding to those individual exposures are provided as a tar file
- 3) The plot showing 2D rectified, wavelength and flux calibrated frames before and after sky subtraction for each exposure in the observing template; it includes the corresponding spectrum marked with a green rectangle
- 4) Rectified, wavelength and flux calibrated 2D frame before sky subtraction.

The primary products contain some header keywords with information related to the OB and the QC process. They are listed in Table 2.

Table 2 FITS keywords added to the primary product

Parameter	Values	Meaning
<i>OB-related information:</i>		
SM_VM	SM or VM	Data taken in Service Mode or Visitor Mode; VM data are less constrained in terms of OB properties; they have no user constraints defined and therefore no OB grades.
OB_GRADE	A/B/C/D; X	Immediate grade given by night astronomer, considering ambient conditions checked against user constraints (A: fully within constraints, B: mostly within constraints (within 10%), C/D: out of constraints, X: VM data or aborted OBs.
OB_COMM<n>	Free text	Any optional comments added by the night astronomer, together with the approximate UT hh:mm (truncated after 200 characters).
<i>QC-related information:</i>		
QCFLAG	e.g. 0001	QC flag composed of 3 or 4 bits, see Table 3.
QC_COMM<n>	Free text	Comments about quality issues

Data Quality

Master calibrations. All used master calibrations have been quality-reviewed and certified at the time of acquisition, as part of the closed Quality Control (QC) loop with the Observatory which also includes the trending of instrument parameters. As part of the certification process for calibration data there is a scoring process to bring non-compliant behaviour of the calibrations to the attention of the QC scientist. All these cases have been handled as part of the certification procedure. Hence, there is reasonable evidence that the master calibrations catch all instrument properties, as relevant for the reduction, correctly and completely.

Review and certification of science products. FORS2 spectra are reviewed and certified by a process that involves automatic scoring. The automatic QC systems scores

- the fulfilment of the calibration plan;
- the saturation of (parts of) the observation;
- the presence of significantly negative pixels ($<-3 \cdot \text{error}$) in the spectra;
- and the quality of the combination process in case of co-added spectra.

The measured values are compared to reference values and scored. A non-zero score flags a potential issue. Since processing is an automated process, no detailed certification is foreseen. However, non-zero scores may trigger random checks and if reviewed, QC comments can be entered. They are intended to be informative, but they don't claim completeness. The QC comments are propagated to the product headers (in the keywords `QC_COMM<n>`).

QC flag. While the QC review is an internal process, there is also a scheme to propagate quality information to the user. The header key "QCFLAG" in the FORS2 products contains a quality flag that is composed of four bits (see Table 3). For each bit, the value 0 means "OK, no concern", while the value 1 means "possible issue".

Table 3 QC flags⁵

Bit	Content (if "yes", value is 0, otherwise 1)	Motivation
#1 – signal-to-noise ratio in the spectrum	average signal-to-noise ratio (keyword SNR) of the single spectrum >3.0 and of the stacked spectrum >2.45	If not, this may indicate a general issue with the spectrum.
#2 – ratio of significantly negative pixels ($<3 \cdot \text{err}$) with respect to all	ratio of negative pixels < 0.05	If not, this may indicate problems with automatic sky subtraction.

⁵ The up-to-date list can be found at http://www.eso.org/observing/dfp/quality/PHOENIX/FORS2/score_bits.txt

good wavelength bins (QUAL=0)		
#3 – seeing	Is the recorded seeing during the observation (keyword HIEARCH ESO TEL IA FWHM LINOBS) between 0.4 and 3 arcsec?	This is an information for the user about the ambient conditions during observation. Data with values below 0.4 probably suffer from undersampling.
#4 – number of the saturated wavelength bins	No or only few saturated pixels, <=10, in the region of the input raw frame from which the spectrum has been extracted	The extracted spectrum or part of the spectrum cannot be used if saturation occurs in input.

The flags #1 to #3 are used if the primary product is a stacked spectrum and all 4 flags if the primary product is a single spectrum.

QC plots and previews. For each science target, a preview plot is available as quick look. It is delivered as ancillary file together with the main product. An example of a plot for a single spectrum is shown in Figure 1, Figure 3, and an example for a combined spectrum in Figure 2.

The plot for a single spectrum, Figure 1, shows the full extracted (in blue) and a re-binned (in red) version of the same spectrum (top panel). Directly below, the spectrum of flux calibrated sky background and the flux calibrated error distribution are plotted. Both spectra are expressed in the flux units [FU], 10^{-16} erg/s/cm²/Å. At the bottom, the extraction window and its median PSF are displayed.

Only the parts of spectra containing scientifically meaningful results (column QUAL=0 in the product table) are plotted. The regions without signal, due to limited wavelength coverage of the observations and/or of the master response (column QUAL=1), are omitted.

FORS2 data product preview

2021-03-04T02:29:10.310

Date: 2021-03-03

Product:	REDUCED_IDP_SCI_LSS	RUN_ID:	105.20DF.001	INS MODE:	LSS	seeing:	0.83 arcsec
OBS_ID:	2990132	ExpTime/s:	1370.0	Binning:	2x2	airmas:	1.04
TPL_ID:	FORS2_lss_obs_off_fast	DET_EXP_NUM:	U1_5	GRI+FLT:	300V+GG435	width:	1.62 arcsec
MJD_OBS:	59277.10359155	Field:	SN2021ckj			RA,DEC:	09:05:51.1 -08:35:09

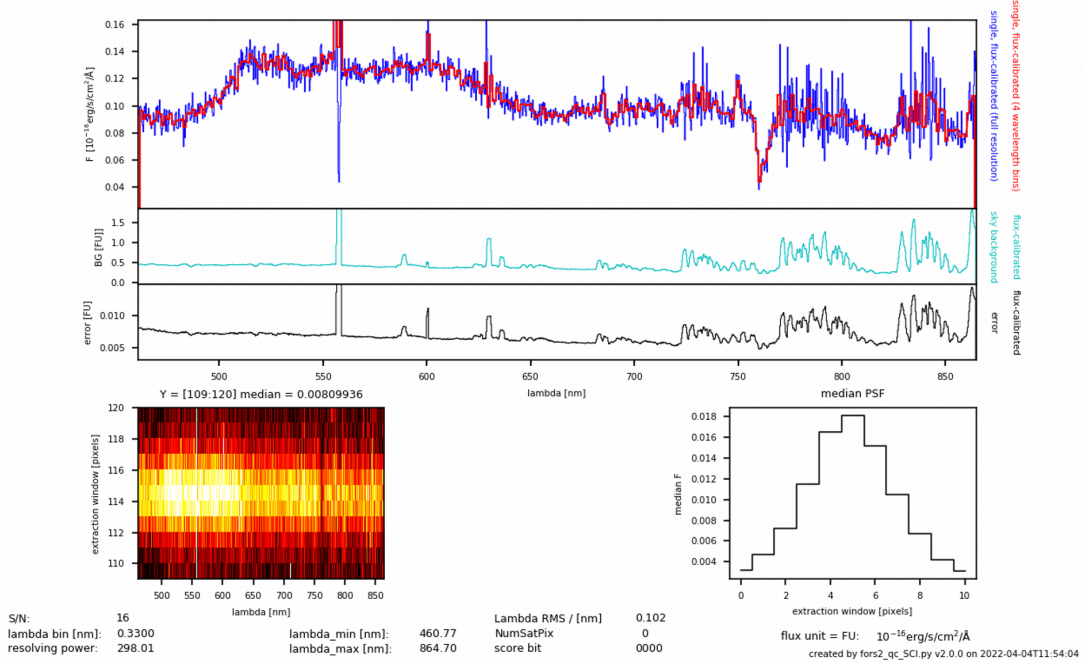
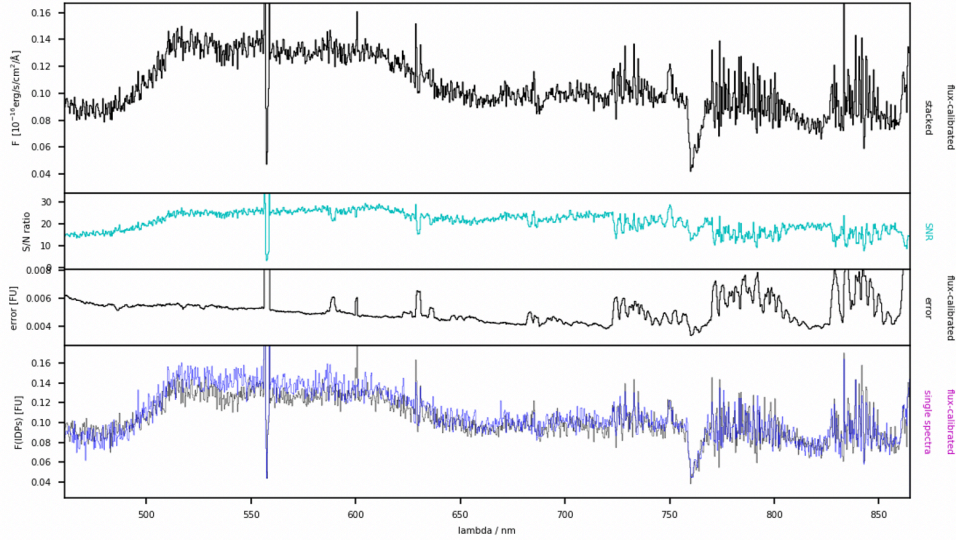


Figure 1 Example of a preview plot associated to a single-exposure spectrum. See text for explanation

The plot for a combined spectrum, Figure 2, has four panels. From the top, first is the flux calibrated, stacked spectrum, the second and third panels show distribution of the S/N ratio and flux calibrated error along the spectrum, while the bottom one shows all input spectra plotted on top of each other. Here also flux of the spectra is expressed in the flux units [FU], 10^{-16} erg/s/cm²/Å.

FORS2 data product preview		2021-03-04T02:29:10.310				Date: 2021-03-03	
Product:	ESOTK_SPECTRUM_IDP_FORMAT	RUN_ID:	105.20DF.001	INS MODE:	L5S	seeing:	1.18 arcsec
OBS_ID:	2990132	TotalExptime/s:	2739.9	Binning:	2x2	airmas:	1.05
TPL_ID:	FORS2_iss_obs_off_fast	DET_EXP_NUM:	U2_2	GRI+FILTER:	300V+GG435	width:	1.62 arcsec
MJD_OBS:	59277.11988171	Field:	SN2021ckj	NumComb:	2	RA,DEC:	09:05:51.1 -08:35:09



SN:	22	lambda_min [nm]:	460.77	flux unit = FU:	10^{-16} ergs/cm ² /Å
lambda bin [nm]:	0.3300	lambda_max [nm]:	864.70		
resolving power:	298.01	score bits:	000		

created by fors2_qc_STACK.py v2.0.0 on 2022-04-04T11:49:58

Figure 2 Example of a preview plot associated to a combined spectrum. See text for explanation

At the top and bottom of each plot, a set of QC parameters applicable to the product are printed:

- the total exposure time of the observation, from header keyword “TEXTPTIME”;
- the number of single-exposure spectra combined (keyword “NCOMBINE”);
- the average S/N ratio of the spectrum;
- the average seeing during the observation [arcsec];
- the average airmass during the observation;
- the width of the slit used for the observation [arcsec];
- the number of saturated wavelength bins in the spectrum;
- the binning in the wavelength direction [nm];
- the resolving power reached during observation;
- minimum wavelength in the spectrum [nm];
- maximum wavelength in the spectrum [nm];
- RMS of the residuals of the wavelength solution [nm];
- and the score bits.

In addition, for a single spectrum, ancillary plot showing the 2D rectified, wavelength and flux calibrated frame before (upper panel) and after (lower panel) sky subtraction for each exposure in the observing template is provided (Figure 3). For easy identification, the green rectangle marks the extracted spectrum position on the sky-subtracted frame. Meaning of the QC parameters printed in the figures is as above.

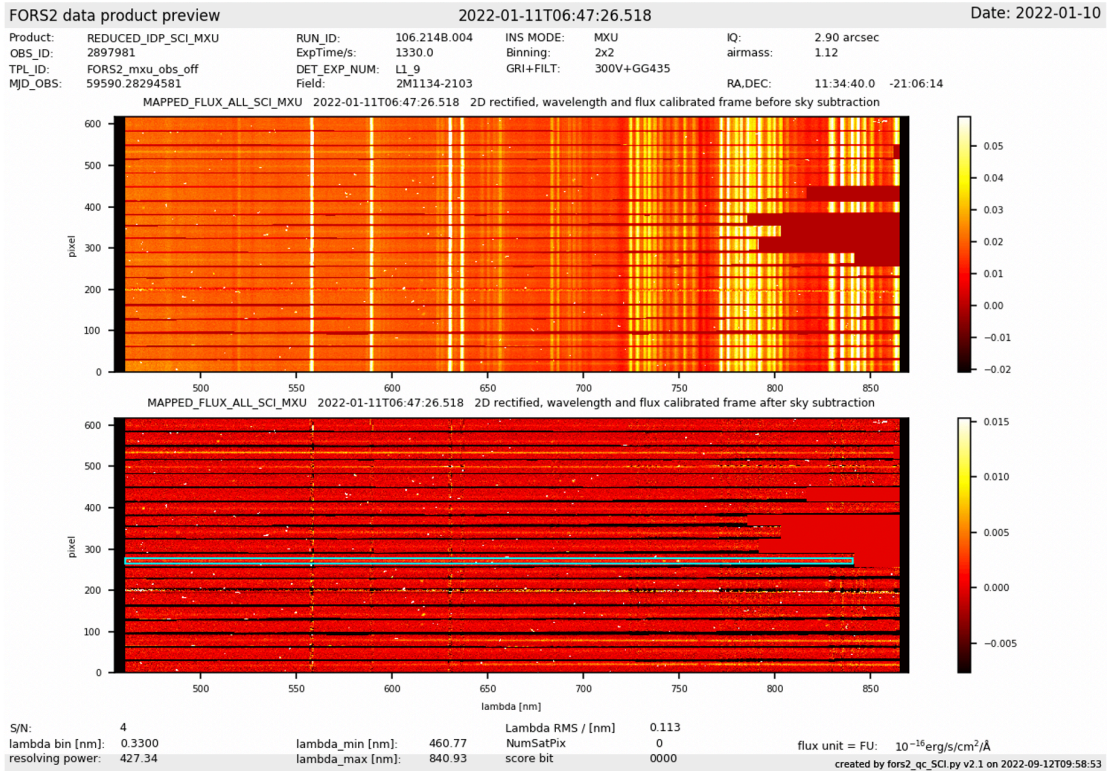
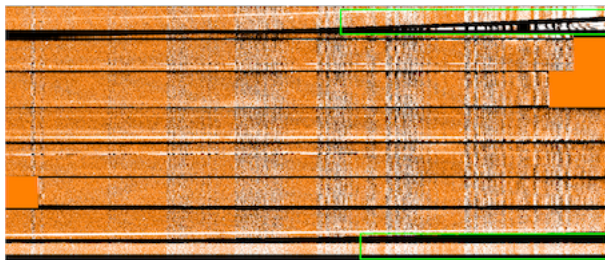


Figure 3 Example of a preview plot showing 2D rectified, wavelength and flux calibrated frame for exposure in the observing template before (top) and after (bottom) sky correction. The green rectangle marks the extracted spectrum. See text for more details.

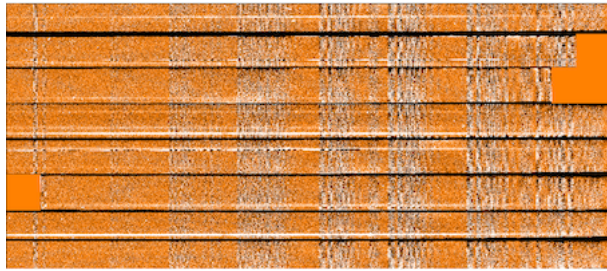
Known Features and Issues

World Coordinate System. The systematic uncertainty of 3 arcsec due to the VLT pointing error (corresponding to 0.000589 degree for each coordinate axis) dominates the uncertainties recorded in the keywords RA_ERR and DEC_ERR.

Slit tracing – badly traced, crooked slits.



Sometimes the slitlets of multi-object spectra are not properly traced in the calibration data, which then results in problems for the science data. Well traced slit are rectangular regions. In the figure to the left we show the sky-subtracted wavelength calibrated 2-dimensional frame for MOS observations, in which the top and bottom slitlets were not correctly traced. The green rectangles mark those regions – the rising black curved line in the top slit and the widening black region above the bottom slit are evidence for bad slit tracing.



The problem was created by an imperfect detection of the arc lamp lines in the calibration data. Lowering the detection threshold for arc lamp lines recovers both slitlets as shown to the left. Such problems can only be solved by reprocessing the raw calibration and science data.

Slit tracing – LSS, slit tracing extended to non-illuminated regions of the detectors.

Occasionally, the master calibrations used for processing science data carry incorrect slit tracing. Example is shown in Figure 4 and Figure 5, where the slits are traced until the bottom of the frame, clearly including the non-illuminated area in the lower part of the detector. As a result, this non-illuminated area is mistakenly included in the sky background estimation. Also, spurious sources can be automatically detected there. Because of those potential problem, affected IDPs are deleted and not distributed to the users.

Wavelength calibration problems – bow-shaped arc or sky lines in LSS. In rare cases, the master calibrations used for processing of the FORS2 spectroscopy IDPs carry sub-standard wavelength calibration, which then affects the science data. For LSS data it can be seen in form of bow-shaped sky lines in the 2D frame.

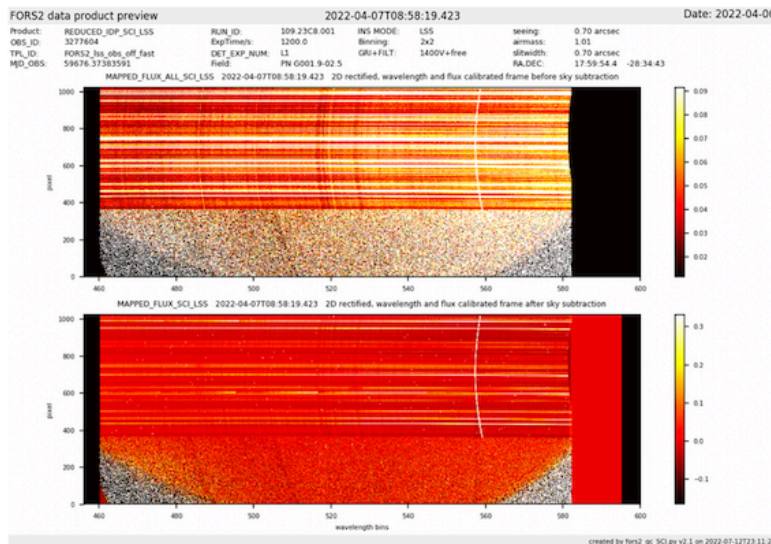


Figure 4 Example of the preview plot for the LSS IDP spectra affected by the wavelength calibration and slit tracing problems. Note the bow-shaped sky lines and the non-illuminated part of the frame included in sky background and source detection.

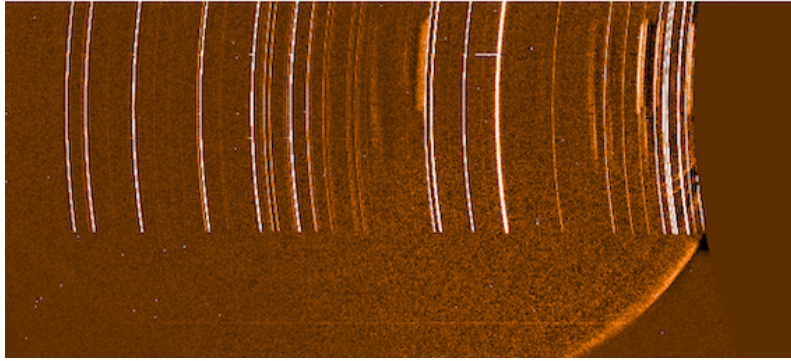


Figure 5 The wavelength master calibration frame used to process the above IDP. As above, note the bow-shaped arc lines and the non-illuminated part of the frame included in the sky background and considered for source detection.

Wavelength calibration problems – flickering/offset arc lines in MOS/MXU, GRIS_150I_no-filter. Often (in about 75% cases), the wavelength calibrations for the GRIS_150I without order sorting filter in MOS and MXU suffer from problem illustrated in Figure 6. The wavelength master calibrations show flickering or shifted arc lines, which indicates bad wavelength correction. This, in turn, affects the science data processed with those master calibrations. Thus, the MOS/MXU science data obtained with GRIS_150I without order sorting filter are not processed and are not distributed to the users.

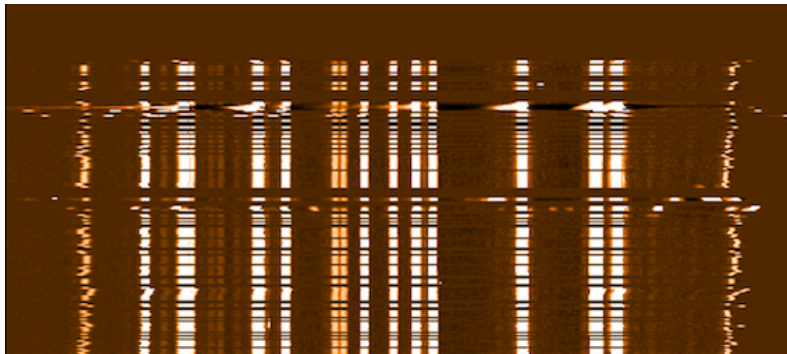
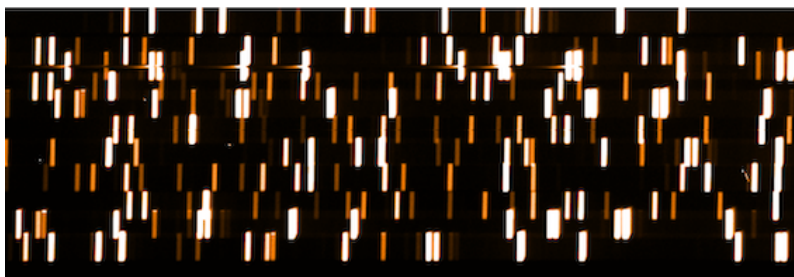


Figure 6 Example of the MOS wavelength calibration frame for the GRIS_150I without order sorting filter. Typical for this setup problems of flickering, shifted arc lines are shown.

Wavelength calibration problems – MXU overlapping slits. In very rare cases, the MXU mask designed by the observer has overlapping slits. See an example of the reduced arc lamp calibration in figure below, where the arc lines belonging to different slits overlap. In such cases, it is likely that the master calibrations carry bad wavelength calibration and the automatically processed science data are affected.



Sky subtraction - method.

There are different methods of sky subtraction implemented in the spectroscopic FORS pipeline: The *skyglobal* method uses the median of the signal in a given wavelength bin of the non-rectified frame as sky signal for that wavelength bin. Because the sky determination is performed before the rectification the sky spectrum is supersampled. This method works only if the resolution along the spatial axis does not vary and the sky background is flat. It is best suited for the sky subtraction of long-slit observations of sparse fields.

For long-slit spectra data with a bright extended object or several bright point sources close to each other, the option *skyglobal*, however, creates an interference like pattern in the fitted sky (see example below), probably caused by non-flat sky background. Therefore, the option *skymedian* is used instead to process long-slit spectra. This sky subtraction uses the median of the signal of all pixels in a wavelength bin of the rectified frame as sky signal for that wavelength bin. It proved to work well also for multi-object spectroscopy data. Thus, the same option is applied for those modes too.

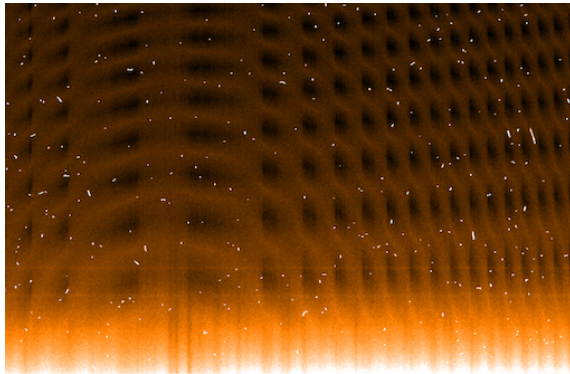
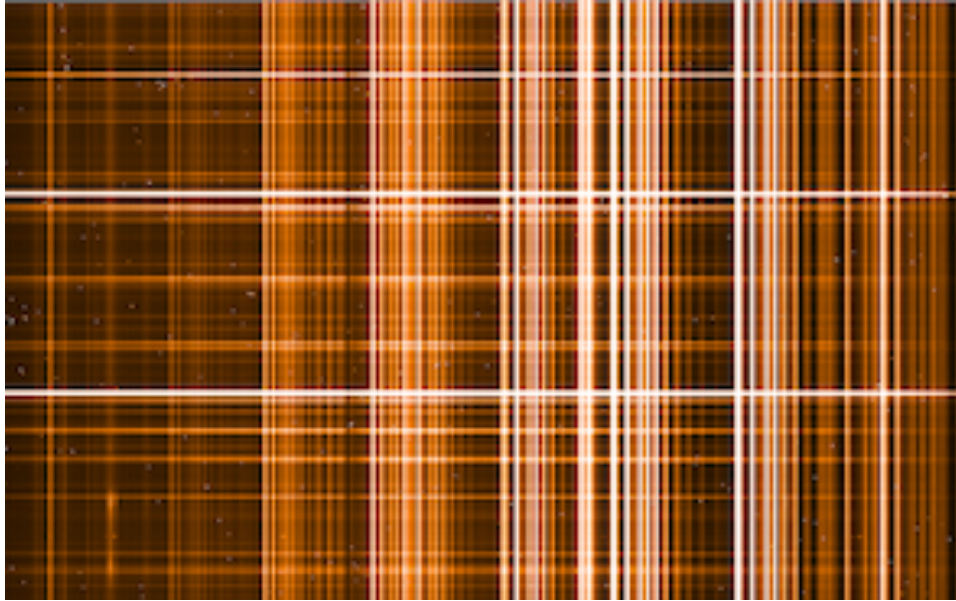


Figure 7 Example of the 2D sky_subtracted LSS frame showing interference like pattern when sky_subtraction method skyglobal was used.

Sky subtraction – spatial gradient in the background present. The sky background spectrum is defined by the median value of the sky for each wavelength pixel of each rectified slit spectrum in the 2D frame after source detection, excluding regions marked for the extraction of objects. This is the most robust sky subtraction method in case of crowded fields or extended objects, while, at the same time, not harming observations of the sparse fields. As all sky subtraction methods implemented in the FORS2 pipeline, it relies, however, on a flat spatial distribution of background light along the slit. In order to remove spatial variations in the sky background caused by the variation of the slit profile, we keep the spatial illumination in the master flat fields. During the flat field correction, higher order variations of the slit illumination profile are then removed, but the linear gradient often remains, possibly caused by different paths of light from the calibration unit and from the sky. If there is a spatial gradient in the sky background the actual sky background will be higher or lower than the fitted one. This can be seen in the example shown below:

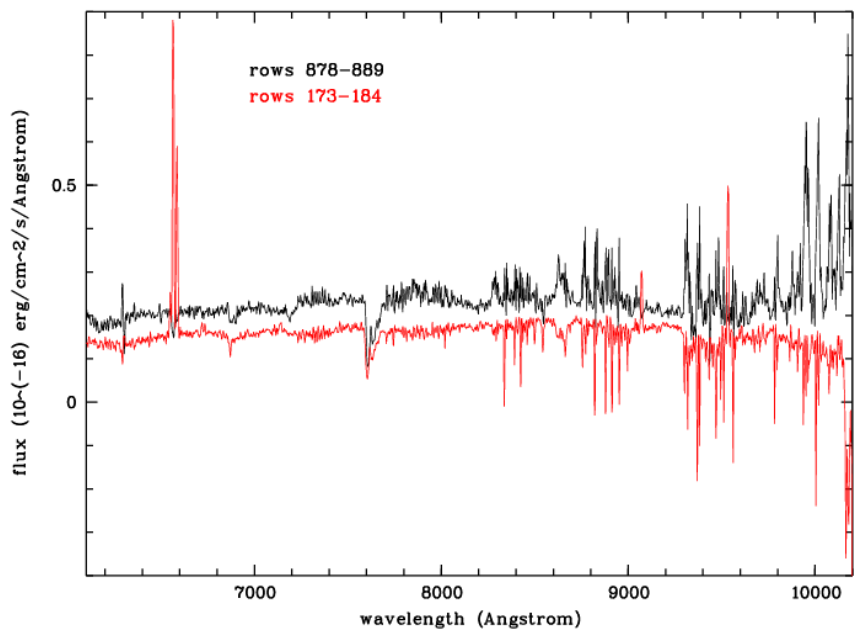


The screen shot above shows the rectified, wavelength calibrated pipeline product for the GRIS_300I+OG590 observations of a crowded field. The screen shot below shows the same frame after sky subtraction. One can clearly see that too much skylight has been subtracted in the lower part (dark sky lines) and too little in the upper part (bright sky lines). Please note that the dynamic range of the image above is 10 times larger than that of the image below.



Below we show two spectra extracted from the sky subtracted frame above, from the **upper part** (in black; too little sky subtracted, sky lines in emission) and from the **lower part** (in red; too much sky subtracted, sky lines in absorption). While the effect

is obvious for these faint spectra it will be more subtle for bright targets.



Sky subtraction – GRIS_300V without order sorting filter stray light.

For the grism GRIS_300V without order sorting filter the stray light problem described in **Flux calibration** causes a strong localized gradient in illumination along the spatial axis. In turn, it causes a strong localized residual slope in the background after sky subtraction (see below), especially for long-slit data.

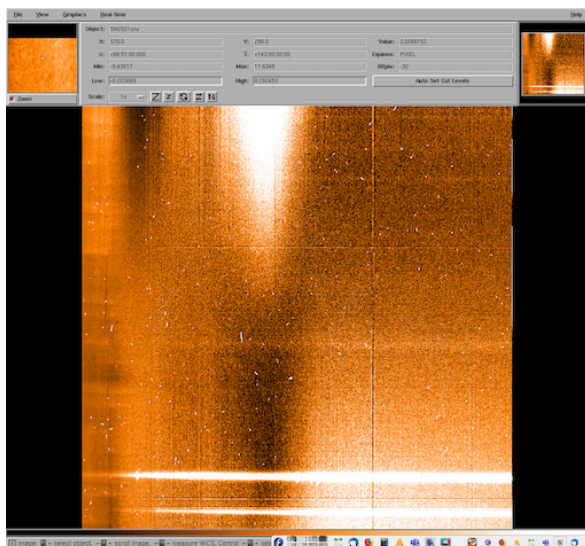
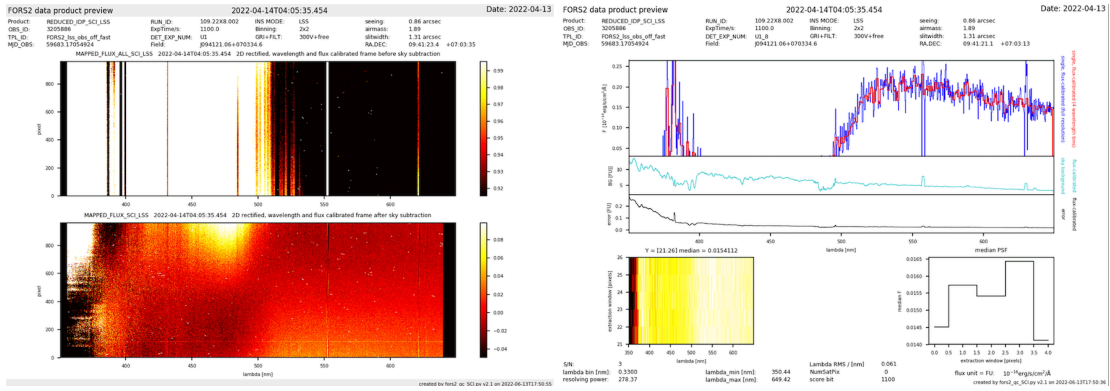


Figure 8 Example of the frame in grism GRIS_300V without order sorting filter showing bright feature in illumination.



The figure above shows an example of the ancillary preview plots of the affected IDP spectrum. The 2D rectified frames (on the left) clearly show the gradient in illumination across the 2D frame, while the spectrum plot (on the right) displays sky-subtracted spectrum where background was overestimated in the blue part. Note, that under-correction of the background cannot be detected. This problem affects all the GRIS_300V (and GRIS_600B) without order sorting filter data.

Mostly zero-flux pixels background spectra. Sometimes the pipeline mistakenly extracts spectra and the estimated background appears to have large majority of the zero-flux pixels. See the data product preview plot below with an example. Note the flat, zero-flux background displayed in green in the horizontal panel, second from the top. Such spectra are spurious detections. The ones that have more than 50% of the zero-flux pixels in the estimated background are deleted and not distributed to the users.

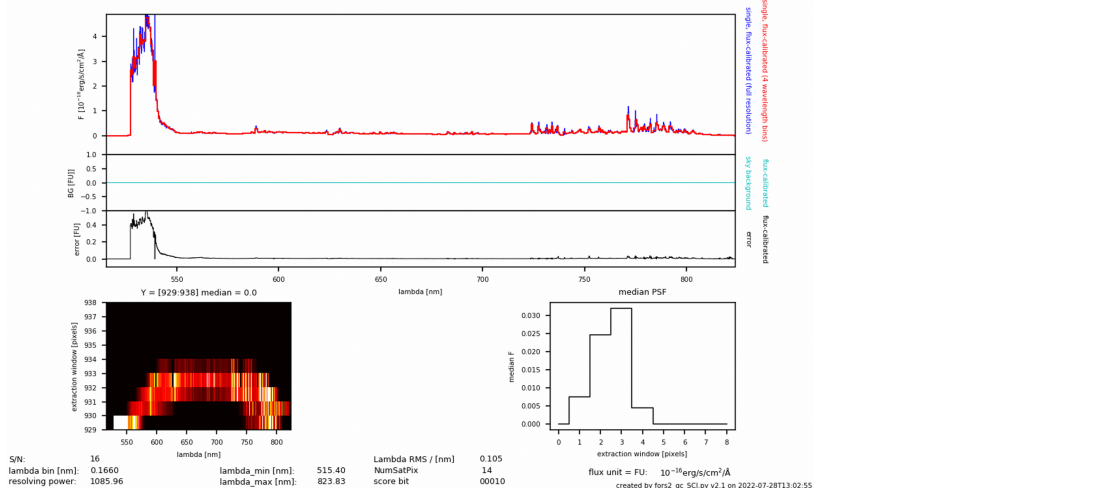


Figure 9 Example of the preview plot of the mostly "zero-flux pixels background" spectrum (plotted in green in the second panel from the top).

Flux calibration. The flux calibration of FORS data is not an absolute one, because the science spectra are usually taken with narrow slits and the slit losses are unknown. The master response curves have been derived from carefully selected individual standard star observations covering the time range January 1, 2015 to May 12, 2019. The *shape* of the response curves has not changed during that time range, so we

expect them to be valid also for later data as long as there are no changes in the instrument. The flux-calibrated spectra are provided in units of 10^{-16} erg/cm²/s/Å.

For the definition of the master response curves for the gratings GRIS_600B and GRIS_300V (without order sorting filter) non-standard flat fields were used to avoid the stray light features like the bright circle seen in the normalized flat field shown below. This feature at the blue end of the wavelength range originates from stray light of the red flat field lamp. For the master response creation, the individual response curves were processed twice, once with flat fields using only the blue lamp and once with flat fields using only the red lamp, and manually merged. The feature is therefore not present in the master response curve but will be present in science data.

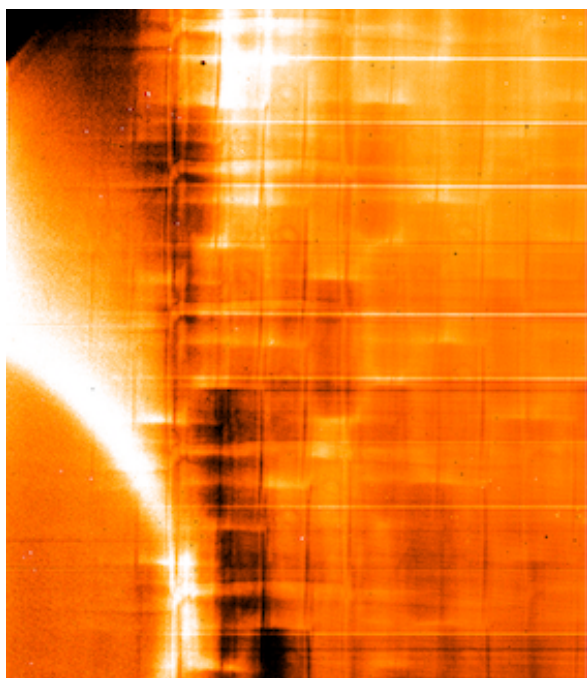


Figure 10 Example of the stray light feature in form of a bright circle seen in the normalized flat field taken in gratings GRIS_300V and GRIS_600B without order sorting filter.

For volume-phased holographic gratings the response depends on the position on the detector along the dispersion axis. This variation affects the flat fields and the science data in the same way and can therefore be corrected by dividing both standard star and science data by the corresponding flat field spectrum. This correction relies on a constant flat field lamp, both in spectral energy distribution (SED) and in flux. This is not the case for the blue flat field lamp of FORS2, which changes its SED and flux level on time scales of minutes. Therefore, the master response curve for the grism GRIS_1200B is not corrected by the flat field SED and is instead provided for different slit positions. Users for whom the relative SED of their targets is particularly important should try to reprocess the spectra and look for the best choice of response determination for their scientific purpose.

Wavelength coverage. For some setups, the wavelength coverage is limited by the 2nd order contamination (e.g., in case of grism GRIS_300V without order-separation-filter) and/or telluric contamination (e.g. gratings GRIS_600z, GRIS_1028z), which can cause a cutoff of the response curve at wavelengths below the full wavelength range of the grism.

Co-added spectra. Multiple exposures on the same target are combined if they have been measured within the same template (using the same guide star), i.e., if the files have the same HIERARCH ESO TPL START header keyword value. The combination is executed independently from the original science goal of the observation. For studying temporal variations, the products from the individual exposures are provided as ancillary files.

Data Format

File Types

The data set for each observation consists of one primary product file, several ancillary FITS files, and one or two preview plots. The number of ancillary files depends on whether the primary product comes from a single exposure or is a co-added spectrum. Table 4 and Table 5 give an overview of the provided files.

Table 4 Primary and ancillary products for spectra from a single exposure

ORIGFILE begins with	Type	Product category HIERARCH ESO PRO CATG and PRODCATG	Number	Primary or ancillary?	Description
F2_SISL	FITS	REDUCED_IDP_SCI_LSS SCIENCE.SPECTRUM	1	Primary	Flux-calibrated spectrum of the single observation in case of LSS
F2_SMSL	FITS	MAPPED_FLUX_ALL_SCI_LSS ANCILLARY.2DSPECTRUM	1	Ancillary	2D rectified wavelength and flux calibrated frame in case of LSS
F2_SISM	FITS	REDUCED_IDP_SCI_MOS SCIENCE.SPECTRUM	1	Primary	Flux-calibrated spectrum of the single observation in case of MOS
F2_SMSM	FITS	MAPPED_FLUX_ALL_SCI_MOS ANCILLARY.2DSPECTRUM	1	Ancillary	2D rectified wavelength and flux calibrated frame in case of MOS
F2_SISX	FITS	REDUCED_IDP_SCI_MXU SCIENCE.SPECTRUM	1	Primary	Flux-calibrated spectrum of the single observation in case of MXU
F2_SMSX	FITS	MAPPED_FLUX_ALL_SCI_MXU ANCILLARY.2DSPECTRUM	1	Ancillary	2D rectified wavelength and flux calibrated frame in case of MXU
	png		2	Ancillary	Preview plots

Table 5 Primary and ancillary products for co-added spectra

ORIGFILE begins with	Type	Product category HIERARCH ESO PRO CATG and PRODCATG	Number	Primary or ancillary?	Description
F2_STCK	FITS	ESOTK_SPECTRUM_IDP_FOR MAT SCIENCE.SPECTRUM	1	Primary	Flux-calibrated, co-added spectrum
F2_SISL	FITS	REDUCED_IDP_SCI_LSS ANCILLARY.SPECTRUM	1..N	Ancillary	Flux-calibrated spectra for each of the N exposures in case of LSS
F2_SMSL	FITS	MAPPED_FLUX_ALL_SCI_LSS ANCILLARY.2DSPECTRUM	1..N	Ancillary	2D rectified wavelength and flux calibrated frame in case of LSS
F2_SISM	FITS	REDUCED_IDP_SCI_MOS ANCILLARY.SPECTRUM	1..N	Ancillary	Flux-calibrated spectra for each of the N exposures in case of MOS
F2_SMSM	FITS	MAPPED_FLUX_ALL_SCI_MOS ANCILLARY.2DSPECTRUM	1..N	Ancillary	2D rectified wavelength and flux calibrated frame in case of MOS
F2_SISX	FITS	REDUCED_IDP_SCI_MXU ANCILLARY.SPECTRUM	1..N	Ancillary	Flux-calibrated spectra for each of the N exposures in case of MXU
F2_SMSX	FITS	MAPPED_FLUX_ALL_SCI_MXU ANCILLARY.2DSPECTRUM	1..N	Ancillary	2D rectified wavelength and flux calibrated frame in case of MXU
	png		1	Ancillary	Preview plot
	tar		1	Ancillary	Tar archive with review plots related to the single spectra that were combined; can be read as tar -{cxt}vf ./<file>.tar

The ORIGFILE product names follow a naming convention which is

F2_<TYPE>_<OBS_ID>_<DP_ID>_<CHIP>_<GRISM><FILTER>_<NN>.fits

See Table 6 for details. An example ORIGFILE name would be

F2_SISM_3121235_2021-03-02T04:04:57.474_C1_300IOG590_04.fits

for a single-exposure spectrum from OB 3121235, observation started at 04:04:57.474 (UT) on 2 March 2021. The archive user may wish to read the ORIGFILE header key and to rename the archive-delivered FITS files accordingly.

In addition to the FITS products, also the preview plots are delivered as ancillary files. They come in the PNG image format and follow the naming conventions

r.FORS2.<DP_ID>_<NNNN>.png

for single-exposure spectra and

r.FORS2.<DP_ID>_s<NN>_<NNNN>.png

for co-added spectra, <DP_ID> is the time stamp of the (first) exposure and <NNNN> is a running number with leading zeros (e.g. ‘0000’, ‘0001’, ...).

Table 6 ORIGFILE naming convention

Component	Description
F2	FORS2 product
<TYPE>	Product type. See Table 4 and Table 5
<OBS_ID>	OB ID of the observation (header key <code>HIERARCH ESO OBS ID</code>)
<DP_ID>	Time stamp in UT of the first exposure of the stack in the format <YEAR>-<MONTH>-<DAY>T<HOUR>:<MINUTE>:<SECOND>.<MILLISECOND>
<CHIP>	Detector identification: C1 – upper (header keyword <code>HIERARCH ESO DET CHIP1 ID = CCID20-14-5-3</code>), C2 – lower (header keyword <code>HIERARCH ESO DET CHIP1 ID = CCID20-14-5-6</code>) detector in the mosaic
<GRISM>	Grism name (header keyword <code>HIERARCH ESO INS GRIS1 NAME</code>)
<FILTER>	Filter name (header keyword <code>HIERARCH ESO INS OPTI7 NAME</code>)
<NN>	Running number (e.g. 01)

File structure and size

The primary FORS2 product is a FITS file with one table extension. The table columns for single-exposure spectra and co-added spectra are given in Table 7 and Table 8, respectively. File sizes of the primary products are between 0.2 and 0.9 MB.

Table 7 Table columns of single-exposure spectra

Column	Unit	Description
WAVE	Å	Wavelength (in air)
FLUX	10^{-16} erg/cm ² /s/Å	Extracted, sky-subtracted flux
ERR	10^{-16} erg/cm ² /s/Å	Error of flux
BGFLUX	ADU/s	Extracted and wavelength-calibrated sky signal, not flux calibrated
FLUX_REDUCED	ADU/s	Extracted, wavelength-calibrated, sky-subtracted science signal, not flux calibrated
ERR_REDUCED	ADU/s	Corresponding error (not flux calibrated)
QUAL	None	Quality. Values above 0 may indicate issues with data, e.g. saturation

Table 8 Table columns of co-added spectra

Column	Unit	Description
WAVE	Å	Wavelength (in air)
FLUX	10^{-16} erg/cm ² /s/Å	Co-added flux
ERR	10^{-16} erg/cm ² /s/Å	Error of flux
FLUX_REDUCED	ADU/s	Co-added, wavelength-calibrated, sky-subtracted science signal, not flux calibrated
ERR_REDUCED	ADU/s	Corresponding error (not flux reduced)
SNR	None	Signal-to-noise ratio of co-added spectrum
SNR_REDUCED	None	Signal-to-noise ratio of co-added, not flux calibrated spectrum
QUAL	None	Quality. Values above 0 may indicate issues with data, e.g. saturation
QUAL_REDUCED	None	Quality, not flux reduced. Values above 0 describe bad pixels.
CONTRIB	None	Number of contributing input spectra
CONTRIB_REDUCED	None	Number of contributing spectra to the not flux calibrated spectrum

Acknowledgement Text

According to the ESO data access policy, all users of ESO data are required to acknowledge the source of the data with an appropriate citation in their publications. Since processed data downloaded from the ESO Archive are assigned a Digital Object Identifier (DOI), the following statement must be included in any publications making use of them:

Based on data obtained from the ESO Science Archive Facility with DOI(s) :

<https://doi.eso.org/10.18727/archive/77> .

All users are kindly reminded to notify Mrs. Grothkopf (esodata at eso.org) upon acceptance or publication of a paper based on ESO data, including bibliographic references (title, authors, journal, volume, year, page numbers) and the observing programme ID(s) of the data used in the paper.