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VLT PROGRAMME

Paranal Observatory

Very Large Telescope

Focal Reducer/Low Dispersion Spectrograph

FORS1+2

User Manual

VLT-MAN-ESO-13100-1543

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VLT Paranal Observatory ⋆ Telephone: +56-55-435000 ⋆ Fax: +56-55-435001

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2.8	Jun. 30, 2004	all	manual under pdf format, updates for new FORS1 Grism 1200g+96, update of gain and ron of FORS1 CCD, update of the plate scales due to the FORS1 and 2 move to UT2 and 1, new Rapid Response Mode, notes about the instrumental linear polarization, the pre-imaging data delivery, the slit along parallactic angle, the calibration plan in LSS Mode

Editors: E. Jehin, K. O'Brien, T. Szeifert Paranal Science Operations, ESO; email: ejehin@eso.org, kobrien@eso.org

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Chapter 1

Introduction

1.1 Scope

The FORS1+2 User's Manual is intended to cover all aspects of the VLT instruments FORS1 and FORS2 and to give comprehensive information on the following topics:

- Overall description of the FORS instruments
- Observing with FORS
- Calibrating and reducing FORS data
- Supplementary Data and Informations about CCDs, filters and grisms

The informations about observation block preparation for FORS with p2pp and mask preparation with FIMS are given in the following supplementary manuals:

- FORS1+2 FIMS Manual (ESO document VLT-MAN-ESO-13100-2308)
- FORS1+2 Templates Manual (ESO document VLT-MAN-ESO-13100-2309)

The knowledge of these manuals is essential for the preparation of proposals and observations with FORS1 and FORS2.

1.2 More Information on FORS

The FORS1+2 User's, FIMS and Templates Manuals are published on the FORS instrument WEB page. Further links to FORS related informations are set on the top of the FORS page:

`http://www.eso.org/instruments/fors/`

Information and software tools for the preparation of service and visitor mode observations with FORS1 and FORS2 are given under:

`http://www.eso.org/observing/p2pp/`

Visiting astronomers will find instructions and hints on the Paranal Science Operations WEB page and the Paranal Observatory home page:

`http://www.eso.org/paranal/`
`http://www.eso.org/paranal/sciops/`

1.3 Contact Information

In case of specific questions related to Service Mode observations and proposal preparation please contact the ESO User Support Group:

usg-help@eso.org

For visitor mode observations please contact the Paranal Science Operations Team:

pso@eso.org

1.4 Acknowledgements

The first edition of this User Manual was delivered by the FORS Consortium which was formed by the Landessternwarte Heidelberg, the University Observatories of Göttingen and Munich in the scope of the FORS contract and finally compiled and edited by G. Rupprecht. Later editions were edited by H. Böhnhardt (until June 2002) and T. Szeifert (until June 2004).

We are very greatfull for the input from the members of the FORS instrument operation team, from the team of the Paranal observatory and last but not least for the feedback from the users.

Chapter 2

Instrument Characteristics

2.1 Overview

Instrument Concept: FORS is the visual and near UV **FO**cal **R**educer and low dispersion **S**pectrograph for the **V**ery **L**arge **T**elescope (VLT) of the **E**uropean **S**outhern **O**bservatory (ESO). It is designed as an all-dioptric instrument for the wavelength range from 330 nm to 1100 nm and provides an image scale of $0''.2$/pixel or $0''.1$/pixel with the 2048×2046 pixels CCD detectors (pixel size of 24×24 μm) of FORS1. Since April 2002 FORS2 is equipped with a mosaic of two 2k×4k MIT CCDs (pixel size of 15×15 μm) with a pixel scale of $0''.125$/pixel or $0''.0625$/pixel. Two versions of FORS have been built and installed on the Cassegrain foci and have been moved to different telescopes in the last years.

The main instrument components shown in Figure 2.1 are: The *Top Section* with the focal plane equipment including the multi object spectroscopy (MOS) unit with 19 movable slits, the longslits, the polarimetry mask (FORS1 only), the MXU mask exchange unit (FORS2 only) and the two calibration units. The *Collimator Section* with the two collimators and the electronic cabinets. The *Filter/Camera Section* with the retarder plate mosaics (FORS1 only), the wheel for the Wollaston prism and optional optical analyzers (filters and/or grisms), the grism wheel and the broadband filter wheel in the parallel beam. Furthermore the camera, the interference filter wheels in the converging beam and the exposure shutter in front of the CCD.

Observing Modes: FORS offers the observing modes tabulated below. While the main observing modes IMG, LSS, MOS, IPOL and ECH are supported for both collimators, some restrictions apply in the modes MXU and MOS of FORS2 and PMOS of FORS1:

FORS1		
direct imaging	IMG	
imaging with occulting bars	OCC	
multi-object spectroscopy with movable slitlets	MOS	
longslit spectroscopy	LSS	
imaging polarimetry	IPOL	
multi-object spectro-polarimetry	PMOS	SR-collimator only
FORS2		
direct imaging	IMG	
imaging with occulting bars	OCC	
multi-object spectroscopy with masks	MXU	SR-collimator only
multi-object spectroscopy with movable slitlets	MOS	SR-collimator only
longslit spectroscopy	LSS	
medium dispersion Echelle spectroscopy	ECH	

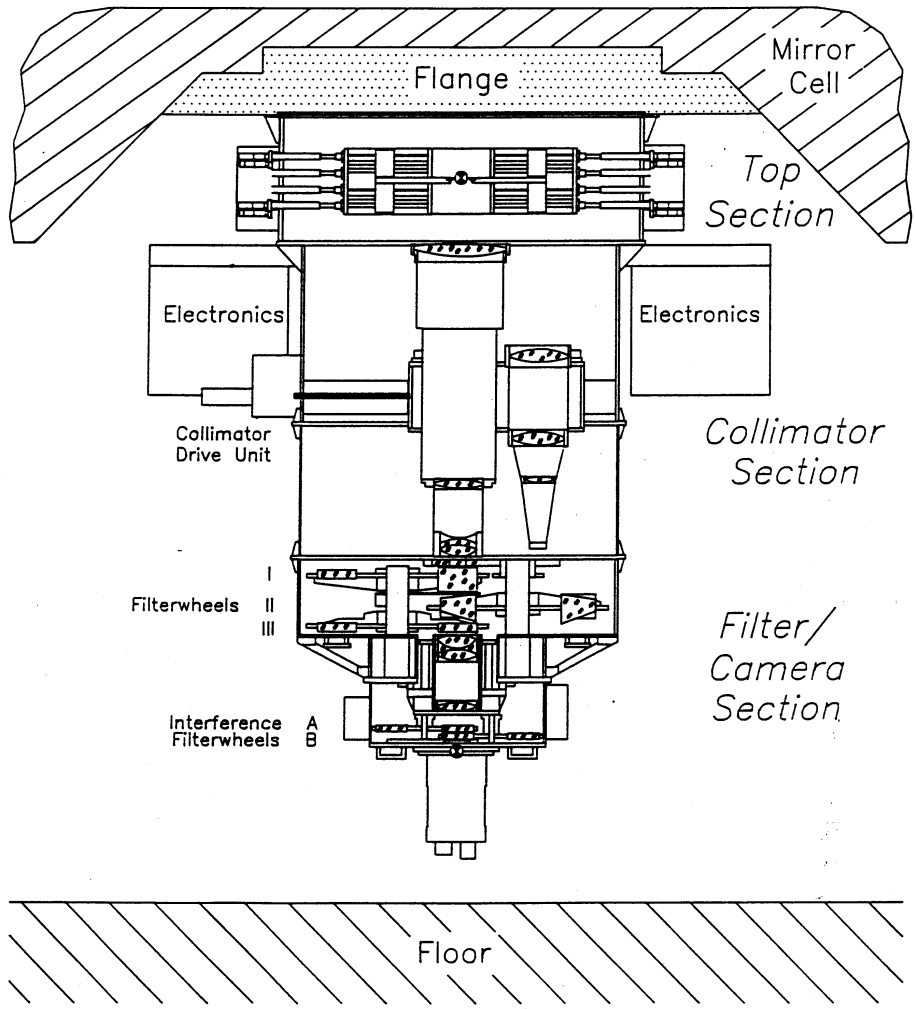

Figure 2.1: Schematic view of the FORS instruments

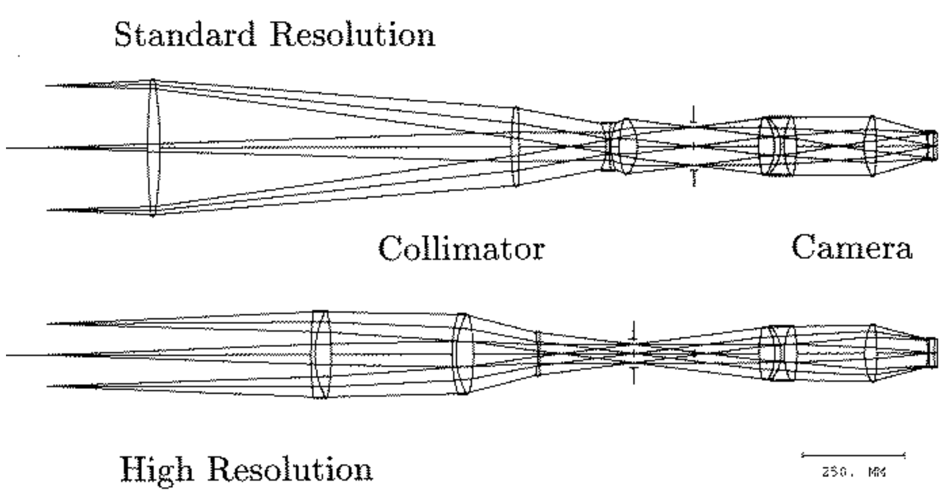

Figure 2.2: Light paths for the standard and high resolution collimators of FORS1 and FORS2.

2.2 Standard Instrument Configurations

Both FORS instruments are operated in the standard configurations with certain opto-mechanical components permanently mounted in fixed positions. This instrument configuration is kept frozen for a given observation period to ensure that all observations in service or visitor mode can be taken at any time without delays due to configuration changes. The summaries of the FORS1 and FORS2 standard configurations are listed below in Tables 2.1 and 2.2. The interference filters given in Table 2.4 and up to 10 MXU masks will be mounted on user request.

Please note that the instrument standard configurations will be only modified in exceptional cases upon request and with the a-priory approval by ESO. The requests should be submitted to usg-help@eso.org before the beginning of an ESO observing period with a brief justification for the changes.

Instrument Location	P2PP Entry Name	Component Name
Focal area	MOS	19 slitlet multi-object spectroscopy unit
	LSS	9 slit longslit mask unit
	polarimmask	Mask unit for imaging polarimetry with HR collimator
Collimator unit	COLL_SR+1	Standard resolution collimator
	COLL_HR+2	High resolution collimator
Retarder swing arm	RETA4+4	Quarter wave plate mosaic
	RETA2+5	Half wave plate mosaic
Wheel 1 (Wollaston wheel)	WOLL_34+13	Wollaston prism
	U_BESS+33	Bessel U filter
	u_GUNN+38	Gunn u filter
	v_GUNN+39	Gunn v filter
	r_GUNN+41	Gunn r filter
	z_GUNN+42	Gunn z filter
	GRIS_600V+94	Grism 600V
Wheel 2 (grism wheel)	GRIS_300V+10	Grism 300V
	GRIS_300I+11	Grism 300I
	GRIS_600B+12	Grism 600B
	GRIS_600R+14	Grism 600R
	GRIS_600I+15	Grism 600I
	GRIS_150I+17	Grism 150I
	GRIS_1200g+96	Grism 1200g
Wheel 3 (broadband filter)	GG375+30	Order sorting filter GG375
	GG435+31	Order sorting filter GG435
	OG590+72	Order sorting filter OG590
	B_BESS+34	Bessel B filter
	V_BESS+35	Bessel V filter
	R_BESS+36	Bessel R filter
	I_BESS+37	Bessel I filter
Wheel 4 (interference filter)	g_GUNN+40	Gunn g filter

Table 2.1: FORS1 standard configuration of opto-mechanical components.

Exchangeable Components: up to 7 and 6 interference filters can be installed in FORS1 and FORS2, respectively, in addition to the standard configuration set-up. For visitor mode observers, the appropriate filter set-up request referring to the available filters of Table 2.4 has to be submitted to the Paranal Science Operations Group at least one day before the start of the observing program. For service mode, Paranal Science Operations will take care of the proper instrument set-up for the observations. Only one copy of each exchangeable interference filter is available. Conflicting requests (if any) will be decided upon by the Observatory. Special rules and recommendations apply for the use of user provided filters: see section 2.3.3.

Filter and Grism Combinations: In general only 1 filter can be used per instrument setup for imaging and 1 grism (plus the recommended order separation filters in table 2.5 if needed) in spectroscopic modes. Combination of 1 grism with 1 of the other filters then the order separation filters are supported if the two components are mounted in different wheels. Combination of two filters at the same time are generally not supported in normal operation since these setups would require testing and software reconfiguration.

Instrument Location	P2PP Entry Name	Component Name
Focal area	MOS	19 slitlet multi-object spectroscopy unit
	LSS	9 slit longslit mask unit
	MXU	mask exchange unit for multi-object spectroscopy with up to 10 masks
Collimator unit	COLL_SR+6	Standard resolution collimator
	COLL_HR+7	High resolution collimator
Wheel 1 (Wollaston wheel)	GRIS_300V+20	Grism 300V
	GRIS_300I+21	Grism 300I
	GRIS_200I+28	Grism 200I
	GRIS_150I+27	Grism 150I
	XGRIS_600B+92	Cross disperser grism 600B
	GRIS_600RI+19	Grism 600RI
	GRIS_600z+23	Grism 600z
Wheel 2 (grism wheel)	GRIS_1028z+29	Grism 1028z
	GRIS_1400V+18	Grism 1400V
	GRIS_600B+22	Grism 600B
	GRIS_1200R+93	Grism 1200R
	GRIS_600I+25	Grism 600I
	z_GUNN+78	Gunn z filter
	EGRIS_110B+98	Echelle grism 110B
Wheel 3 (broadband filter)	GG375+80	Order sorting filter GG375
	GG435+81	Order sorting filter GG435
	OG590+32	Order sorting filter OG590
	B_BESS+74	Bessel B filter
	V_BESS+75	Bessel V filter
	R_SPECIAL+76	Special R filter
	I_BESS+77	Bessel I filter
Wheel 4 (interference filter)	FILT_465_250+82	Order sorting filter 465/250
	U_SPECIAL+73	special U filter

Table 2.2: FORS2 standard configuration of opto-mechanical components.

2.3 Direct Imaging — IMG and OCC modes

2.3.1 Basic Characteristics of the Imaging Optics

Field of View, Pixel Resolution, Transmission, Image Quality: FORS reduces the VLT Cassegrain image scale of 528 μm/arcsec to 0.″2/pixel with the standard resolution collimator and 0.″1/pixel with the high resolution collimator and the 24 μm pixels of the 2048×2046 Tektronix CCD detector of FORS1. In case of FORS2 to 0.″125/pixel and 0.″0625/pixel for the 15 μm pixels of the MIT CCD mosaic. Please take the accurate scales and informations about the image field distortion from section 4.2. Sky concentration effects will be small and negligible for flat-field and photometric calibrations.

	Standard Resolution	High Resolution
Image Quality	80 % in 0.″2	80 % in 0.″1
	within 4.′0	within 2.′0
collimator focal length	1233 mm	616 mm
camera focal length	280 mm	280 mm
final f-ratio	3.13	6.25
FORS1		
Pixel Scale	~0.″2/pixel	~0.″1/pixel
Field of View	6.′8×6.′8	3.′4×3.′4
FORS2		
Pixel Scale	~0.″126/pixel	~0.″0632/pixel
Field of View	6.′8×6.′8	4.′2×4.′2

Table 2.3: Optical properties of FORS

Field vignetting and detetor geometry with the larger FORS2 CCD: The field of view of FORS2 with MIT CCDs is restricted by the MOS unit in the focal plane of the unit telescope to about 6.8 arc-minutes for the standard resolution collimator. In case of the high resolution collimator the corners of the field of view are vignetted by the camera lenses. The two CCDs are mounted slightly offset by 33 arc-seconds for operational reasons. The center of the field of view will fall on y-pixel ~260 of the upper "master" CCD for unbinned standard resolution mode. Images showing the respective vignetting pattern for the standard (MOS) and high resolution collimator mode can be found in appendix G of this manual.

High resolution imaging with the FORS2 CCD mosaic: With the higher sampling of the MIT CCDs of 0.″125/pixel for the unbinned 15μm pixels it will be possible to operate with the standard resolution collimator down to seeing values of about 0.″35 without performance losses in respect to observation with the high resolution collimator. Below seeing values of 0.″3 the high resolution collimator is expected to improve the image quality in a significant way.

2.3.2 The FORS Filter Set

Standard Broadband Filters: FORS provides positions for 7 broadband filters in any of the three wheels of the parallel beam section and for 8 interference filters in two wheels of convergent beam section. Presently available standard filter sets for FORS1 are Bessel U, B, V, R, I, Gunn u, v, r, z, and some order separation filters (see Table 2.1). FORS2 has Bessel B, V, I and R pass-band filters, Gunn z as well as order separation filters (see Table 2.2). The special U and the Gunn g filters are interference filters and have to be mounted into the interference filter wheels. The special R band filter and the Bessel I filter of FORS2 show internal fringes at a faint level. In case of the Bessel I the internal fringes can be only seen with the IR optimized MIT detectors. In both cases the typical shape of the pattern is circular and off-axes. The complete list of filters together with the transmission curves are presented in appendix B of this manual.

Order Separation Filters: the order separation filters are foreseen for spectroscopic applications in the first place, but they are also available for imaging exposures. They have an edge-shape transmission curve with cut-off wavelength designed to match the respective grisms for spectroscopy. The order separation filters are installed in the parallel beam of the instruments (except of the box shape filter FILT_465_250+82 which is in convergent beam of FORS2).

Interference Filters: the standard interference filters available for FORS1 and FORS2 are centered on important emission lines and on wavelengths 5 and 10% longer. The interference filters are located in the convergent beam in the camera and have a diameter of 115 mm. Their wave front error is less than $\lambda/4$ within 25 mm.

P2PP entry	Filter type
OII+44	O II filter
OII/4000+45	O II filter redshifted by 4000 km/s
OII/8000+46	O II filter redshifted by 8000 km/s
HeII+47	He II filter
HeII/3000+48	He II filter redshifted by 3000 km/s
HeII/6500+49	He II filter redshifted by 6500 km/s
OIII+50	O III filter
OIII/3000+51	O III filter redshifted by 3000 km/s
OIII/6000+52	O III filter redshifted by 6000 km/s
HeI+53	He I filter
HeI/2500+54	He I filter redshifted by 2500 km/s
HeI/5000+55	He I filter redshifted by 5000 km/s
OI+56	O I filter
OI/2500+57	O I filter redshifted by 2500 km/s
OI/4500+58	O I filter redshifted by 4500 km/s
H_Alpha+83	H Alpha filter (replacement for H_Alpha+59)
H_Alpha/2500+60	H Alpha filter redshifted by 2500 km/s
H_Alpha/4500+61	H Alpha filter redshifted by 4500 km/s
SII+62	S II filter
SII/2000+63	S II filter redshifted by 2000 km/s
SII/4500+64	S II filter redshifted by 4500 km/s
SIII+65	S III filter
SIII/1500+66	S III filter redshifted by 1500 km/s
SIII/3000+67	S III filter redshifted by 3000 km/s
FILT_485_37+68	special intermediate-band filter
FILT_691_55+69	special intermediate-band filter
FILT_815_13+70	night sky suppression filter
FILT_834_48+71	night sky suppression filter
z_SPECIAL+43	Special z-band filter (width 20nm)
FILT_917_6+88	Special z-band filter (width 6nm)
FILT_530_25+84	Munich intermediate-band filter
FILT_500_5+85	Munich O III filter
FILT_503_5+86	Munich O III filter redshifted by 1800 km/s

Table 2.4: Exchangeable filter set for both FORS instruments

The intrinsic transmission curves of the narrow band filters has approximately Gaussian shape. The central wavelengths of the interference filters depend on the tilt angle of the incident beam. Therefore all interference filters of FORS are used in the convergent beam only, to minimize the field dependence of the filter curves. For the given focal ratio of FORS the minimum recommended filter resolution $\lambda/\Delta\lambda$ will be 100 (SR) and 400 (HR collimator). Filter curves more narrow than this will be convolved and only the transmission will drop down! The measured transmission parameters of the narrow band filters for the convergent beam are summarized in Table B.2.

Medium band Interference Filters: a few intermediate band filters are available to be shared with both FORS instruments. Table B.2 lists the filter names and the transmission characteristics, Figure B.3 shows the transmission curves of the filters.

Image Offsets: The V_BESS+75 filter of FORS2 is known to show a residual wedge angle which would displace the images slightly. This filter should not be used for target acquisitions. Other sources of image offsets would be the relatively small flexures of FORS and the atmospheric dispersion. The later is corrected by the atmospheric dispersion corrector, such that there should be no significant image offsets between the telescope guiding system and the respective images taken with FORS for zenith distances of up to 45 degrees (it is partly correcting at even higher zenith distances).

2.3.3 User Provided Filters

The installation of user provided filters in the FORS instruments is subject of approval by the Director of Paranal and will only be considered upon recommendation of the ESO program committees (OPC and DDTC). The filters and their mounts must comply optically and mechanically with the specifications of the standard FORS filters and mounts (which can be requested from the Instrumentation Division).

The diameter of user provided filters shall not be smaller than 138mm (parallel beam) to avoid vignetting which would be equivalent to a reduction of the main mirror diameter. Interference filters (115±0.25mm) are used in the converging beam of the camera. Their spectral resolution shall not exceed 100 (SR mode) or 400 (HR mode). There is a limited number of filter mounts (for converging beam filters only) available in Garching to be sent to the users on request.

The filters, fully assembled in the mounts, must be made available to the Paranal Observatory at the latest 6 weeks before the start of the respective observing program execution. They will be installed in the instrument and tested for compatibility and focusing during this time. The Observatory reserves the right not to allow special filters to be mounted for observations in case of technical and/or operational problems. User-provided filters are usually not allowed for FORS service mode observing programs.

2.3.4 HR Collimator Field Stop

For HR observations in imaging mode the MOS slit arms are also used to form a field stop mask to limit the field in the focal area of the instrument and thus to reduce stray light.

2.3.5 Occulting Masks

Individual arms of the MOS unit can be used in the direct imaging modes (this includes also imaging polarimetry) to block light from bright objects next to very faint ones. In this case, the use of the FIMS software tool is mandatory for the preparation of the observations; for details see the FORS1+2 FIMS Manual.

2.3.6 Image Motion due to Flexure

Image motion due to instrument flexure under gravity is below 0.25 pixel over a 1 hour exposure with the standard and a 2 hour exposure with the high resolution collimator for zenith distances less then 60°.

2.4 Spectroscopy

Spectroscopy Modes: the FORS instruments offer four spectroscopic observation modes: LSS, MOS, MXU and ECH. With the exception of MXU and MOS spectroscopy of FORS2 (SR collimator only), all spectroscopy modes are supported for both collimators. The HR collimator will project the slit image with the double size to the CCD with respect to the SR mode and the spectral resolution in HR mode will be therefore reduced by a factor of two. A variety of grisms with different wavelength ranges and dispersions is available (see Table 2.5). The grisms can be combined with filters for order separation or more specialized settings. The dispersion direction is along the X direction of the CCD in all spectroscopic modes. The camera focus is set automatically depending on the grism-filter combination in the optical path of the instrument.

Usable Field for Spectroscopy: for objects close to the edge of the field of view (in the direction of dispersion), a part of the spectrum will not reach the CCD. Therefore, the typical usable field of view for spectroscopy with the standard and high resolution collimators will be reduced in dispersion direction.

2.4.1 Grisms and Order Sorting Filters

Normal Grisms: two sets of normal grisms are available for the two instruments which cover the full operational wavelength range of FORS with essentially three different resolutions: 230 Å/mm, 110 Å/mm, 45 to 50 Å/mm (see Table 2.5). Each instrument has a baseline set of identical grism replica which support the same spectroscopy options: GRIS_600B+12/22, GRIS_600I+15/25, GRIS_300V+10/20, GRIS_300I+11/21, GRIS_150I+17/27. In addition, 3 more normal grisms exist in single copies: GRIS_600V+94, GRIS_600R+14 in FORS1 and GRIS_200I+28 in FORS2. All grisms are mounted in the grism or Wollaston wheels of the parallel beam section.

Holographic Grisms: in addition to the normal/standard grisms some medium resolution high throughput grisms are available with FORS2: GRIS_1400V+18, GRIS_1200R+93, GRIS 1028z+29, GRIS_600RI+19 and GRIS_600z+23 and FORS1: GRIS_1200g+96. These grisms are based on volume-phased holographic gratings which are cemented between two glass prisms (see Figures C.2 for the 1st order throughput measurements).

A special note about grisms 600RI and 1400V of FORS2: Due to manufacturing errors, a tilt of the light beam is induced for grisms GRIS_1400V+18 and GRIS_600RI+19 which shifts the spectrum on the detector in Y direction by ∼111 and ∼272 pixels (unbinned 15 micron pixels, as compared to the object position in the through-slit image). There should be no part of the spectrum lost for grism 1400V since the MIT CCD mosaic is large enough to receive all the tilted light. For grism GRIS_600RI+19 the expected consequences will be that the uppermost 21 arc-seconds of the field of view will fall off the CCD in SR-mode.

Order Separation Filters: order sorting filters are available to allow for the suppression of spectral order overlaps in the spectra. Order separation filters are installed in the broadband filter wheel with the exception of the blue band-pass filter FILT_465_250+82 to be used for 2nd-order observations and the suppression of scattered light in Echelle mode.

Other FORS Filters: normal broad-band, medium and narrow-band filters can also be combined with the grisms, but only one filter at a given time and only filters which are not mounted in the same wheel as the user selected grism.

Grism and Filter Transmission: efficiency curves of the available grisms are presented in Appendix C. For the filter characteristics see Appendix B.

2.4.2 Relative Astrometric Accuracy Requirements for Spectroscopy

Highly accurate relative astrometry is required for any observing mode which will make use of FIMS or blind offset acquisitions. The mask preparation with FIMS requires input images which are astrometrically corrected within the definitions and precision given below. DSS images will, in almost all cases, not be suitable for the task. In general the relative astrometry must be known better than 1/6 of the slit widths all over the field of view. Relative astrometry here means that the slit positions must be known relative to those of reference stars in the field of view with the given precision. To achieve such an astrometric calibration based on stars in your field is difficult. It is recommended to cross check the values for the image scale and field distortion in other fields (whenever possible in fields with astrometric standard stars[1]).

All these relative astrometric calibrations are not required, if your FIMS preparation is based on pre-images taken with

[1]see eg. UCAC1, Zacharias et al. 2000, AJ 120, p2131 or SDSS, Stoughton et al. 2002, AJ 123, p485

any of the FORS instruments. It is strongly recommended to search in the VLT Science Archive (`http://archive.eso.org`) for released FORS imaging data.

Restrictions for pre-images to be used for the mask preparations: The target acquisition procedures were reviewed and based on the latest astrometric measurements there should be no more restrictions in using FORS1, FORS2 and other astrometrically corrected images (with world coordinate systems defined in the fits headers) to prepare masks for any FORS instrument. The fits headers of FORS1 images taken before March 22, 2003 would need to be corrected in the fits headers. This should be discussed with the observatory staff (usg-help@eso.org) before submitting the respective masks.

instrument	pre-imaging source	alignment quality
FORS1	FORS1 (after March 22, 2003)	optimum
FORS1	FORS2	optimum
FORS1	other images & catalogs	optimum
FORS2	FORS2	optimum
FORS2	FORS1 (after March 22, 2003)	optimum
FORS2	other images & catalogs	optimum

2.4.3 Instrument Flexures

The image motion due to instrument flexure under gravity is less then 0.25 pixel over a 1 hour exposure with the standard and a 2 hour exposure with the high resolution collimator for zenith distances less then 60°. Arcs and flat are however taken at daytime and at the zenith. This will introduce an offset between night time calibration based on telluric emission lines and day time calibrations based on arc lines depending on the zenith distance and the absolute angle of the Cassegrain rotator. The passive flexure compensation of the FORS instruments, based on support struts on the camera section was optimized down to the following small but not negligible image motions between zenith and the given zenith distances:

zenith distance	COLL_SR	COLL_HR
0°		
15°	<0.3pxl	<0.15pxl
30°	<0.5pxl	<0.25pxl
45°	<0.7pxl	<0.35pxl
60°	<0.9pxl	<0.45pxl

In all standard configurations telluric emission lines will fall into the wavelength range of FORS. However with GRISM_600B and off-axes slits toward the right/red side of the instrument the telluric lines may fall out of the wavelength range.

Another effect which will shift the dispersion solution is the mask positioning error which will be much smaller. The mask positions can be reproduced within 5 to 10 microns compared to the telescope image scale of 528 microns per arc-second. While observing point sources the centering of the target on the slit will be the main source of uncertainty.

2.4.4 Longslit Spectroscopy — LSS mode

Longslit Mask LSS: A mask providing 9 longslits with high quality slit edges is available for the focal area of FORS; they have a common slit length of 6.′8 and fixed slit widths as given in Table 2.6. The approximate offsets of the slits to the central slit of 0.′′28 are given in the same table as offsets on the sky and on the CCD (collimator dependent). The actual slit for the observation is selected by a decker mask. See appendix E.2 for the orientation. The actual LSS slitpositions on the CCD depend also on the mounting reproducibility of the CCD dewar and may change slightly when the CCD dewar is mounted back to the instrument after maintenance. However, the centering accuracy of the objects on the slits is not affected by these variations in the on-chip slit positions.

Target Acquisition on Slit: target acquisition on the LSS mask slit can be done in the following ways:

1. in case of fairly bright objects, the “fast” mode acquisition can be used. This basically involves a direct image of the target field and a mouse click on the object.

2. for faint sources the acquisition can be done with blind offsets in “fast” mode - the offsets will be executed after centering a reference star on the slit (template FORS1/2_lss_obs_slit_fast).

Grism	$\lambda_{central}$ [Å]	λ_{range} [Å]	dispersion [Å/mm]/[Å/pixel]	$\lambda/\Delta\lambda$ at $\lambda_{central}$	filter
FORS1 standard					
GRIS_600B+12	4650	3450 - 5900	50/1.20	780	
GRIS_600V+94 (6)	5850	4650 - 7100	49/1.18	990	GG375+30
GRIS_600V+94 (6)	5850	4650 - 7100	49/1.18	990	GG435+31
GRIS_600R+14 (5)	6270	5250 - 7450	45/1.08	1160	GG435+31
GRIS_600I+15 (5)	7950	6900 - 9100	44/1.06	1500	OG590+72
GRIS_300V+10 (1)	5900	3300 - (6600)	112/2.64	440	
GRIS_300V+10 (1)	5900	3850 - (7500)	112/2.64	440	GG375+30
GRIS_300V+10	5900	4450 - 8650	112/2.69	440	GG435+31
GRIS_300I+11	8600	6000 - 11000	108/2.59	660	OG590+72
GRIS_150I+17 (1)	7200	3300 - (6500)	230/5.52	260	
GRIS_150I+17 (1)	7200	3850 - (7500)	230/5.52	260	GG375+30
GRIS_150I+17 (1)	7200	4450 - (8700)	230/5.52	260	GG435+31
GRIS_150I+17	7200	6000 - 11000	230/5.52	260	OG590+72
FORS1 volume phased holographic					
GRIS_1200g+96	4880	4310 - 5490	24.4/0.59	1650	

Grism	$\lambda_{central}$ [Å]	λ_{range} [Å]	dispersion [Å/mm]/[Å/pixel]	$\lambda/\Delta\lambda$ at $\lambda_{central}$	filter
FORS2 standard					
GRIS_600B+22	4650	3300 - 6210	50/0.75	780	
GRIS_600I+25 (5)	7950	6630 - 9390	44/0.66	1500	OG590+32
GRIS_300V+20 (1)	5900	3300 - (6600)	112/1.68	440	
GRIS_300V+20 (1)	5900	3850 - (7500)	112/1.68	440	GG375+80
GRIS_300V+20	5900	4450 - (8700)	112/1.68	440	GG435+81
GRIS_300I+21	8600	6000 - 11000	108/1.62	660	OG590+32
GRIS_200I+28 (2)	7450	5600 - 11000	162/2.43	380	
GRIS_150I+27 (1)	7200	3300 - (6600)	230/3.45	260	
GRIS_150I+27 (1)	7200	3850 - (7500)	230/3.45	260	GG375+80
GRIS_150I+27 (1)	7200	4450 - (8700)	230/3.45	260	GG435+81
GRIS_150I+27	7200	6000 - 11000	230/3.45	260	OG590+32
FORS2 volume phased holographic					
GRIS_1400V+18 (4)	5200	4560 - 5860	20.8/0.31	2100	
GRIS_1200R+93	6500	5750 - 7310	25.0/0.38	2140	GG435+81
GRIS_1028z+29	8600	7730 - 9480	28.3/0.42	2560	OG590+32
GRIS_600RI+19 (4)	6780	5120 - 8450	55/0.83	1000	GG435+81
GRIS_600z+23	9010	7370 - 10700	54/0.81	1390	OG590+32
FORS2 - 2nd order					
GRIS_600I+25 (3)	4250	3690 - 4880	19/0.29	1830	FILT_465_250+82
GRIS_600z+23 (3)	4660	3890 - 5460	25/0.38	1530	FILT_465_250+82

Table 2.5: Characteristics of the FORS grisms. The table lists the resolution $\lambda/\Delta\lambda$ achieved for a 1″ slit in case of the standard resolution collimator and for a 0.5″ slit in the case of the high resolution collimator at the given central wavelength in column 2. The wavelength range corresponds to a slit which is located in the field center (see Table 2.6 for long slit x-offsets). A value in parenthesis indicates the approximate wavelength at which order overlap occurs. Off-center slit positions (for instance with MOS, MXU or other LSS longslits) shift the wavelength range on the CCD accordingly.
(1) The start wavelength of the 2nd order overlap is given in parenthesis.
(2) This order separation filter (OG550) is cemented to the grism itself.
(3) Low performance is expected since the grisms are not optimized for 2nd order observations.
(4) This grism produces a Y offset on the CCD, see section 2.4.1 for details.
(5) Higher throughput volume phased holographic grisms are available on FORS2
(6) The selection of filters GG375 or GG435 (grism 600V) is only important for offset (P)MOS slits

Longslits of FORS1/2					
slit width	slit offsets	FORS1 in 24μm pixels		FORS2 in 15μm pixels	
	sky	CCD SR-mode	CCD HR-mode	CCD SR-mode	CCD HR-mode
2.″5	45.″3	-226	-453	-362	-723
1.″60	34.″0	-170	-340	-272	-544
1.″0	22.″6	-113	-226	-182	-362
0.″51	11.″3	-57	-113	-91	-182
0.″28	0.″0	0	0	0	0
0.″40	-11.″3	57	113	91	182
0.″70	-22.″6	113	226	182	362
1.″31	-34.″0	170	340	272	544
2.″0	-45.″3	226	453	362	723

Table 2.6: Slit widths of the FORS1/2 longslits and approximate offsets relative to the central slit (in pixels on the CCD). The exact values are slightly different for both instruments and depend also on the reproducibility of the CCD position after maintenance.

2.4.5 Multi-Object Spectroscopy with Movable Slitlets — MOS Mode

MOS Concept: in the MOS mode up to 19 objects can be observed simultaneously by means of slitlets which are formed each by two blades mounted on opposite carriers. The slitlets can be moved by linear guides to any position along the dispersion direction in the field of view. The slit width of the single MOS slits can be adjusted to any user defined value. By combining the linear positioning of the slitlets in the focal area with a rotation of the FORS instrument around its optical axis a wide variety of object configurations can be realized.

MOS Slitlets: 19 movable slitlets are available per instrument. Even-numbered slitlets are 20″ long[2], odd-numbered slitlets 22″ (projected on the sky). The approximate Y-position within which objects should be positioned is slightly decreased by parasitic light falling between the slitlets.

Collimator Constraints: MOS mode with the high resolution collimator is only supported with FORS1. The standard resolution collimator allows to use all 19 MOS slitlets, with the high resolution collimator on FORS1 only slitlets 6 to 14 can be used.

Target Acquisition with MOS: MOS observations must be prepared using FIMS. Reference stars are used to position the telescope and instrument such that the spectroscopy targets are in the slitlets of the predefined MOS mask.

2.4.6 Wide Slit Spectro-Photometry — SPECPHOT mode

For high accuracy spectro-photometry a supplementary mode SPECPHOT was introduced which is used mostly for the monitoring of the instrument response in the framework of the FORS calibration plan. The MOS slits are opened to 5 arcsecs slit width. By default the slits will be placed to the center of the field in dispersion direction. Alternatively the slits can be set to to the position of the FORS longslits or to any user defined offset position to the edge of the field of view.

2.4.7 Multi-Object Spectroscopy with masks on FORS2 — MXU mode

FORS2 has a Mask eXchange Unit (MXU) built into its top section. This MXU is a magazine holding up to 10 masks (made of black painted stress relieved invar sheets of 0.21 mm thickness) laser-cut by the Mask Manufacturing Unit (MMU) of the VIMOS instrument. The purpose of the MXU mode is to allow more objects to be observed simultaneously than with the 19 slitlets MOS unit. Furthermore it gives more freedom in choosing the location, size and shape of individual slitlets. MXU spectroscopy is only offered in the standard resolution mode of FORS2.

It is recommended that observers in Visitor Mode prepare the masks design or get familiar with MXU mask preparation before their arrival on Paranal (usually 3 days before the start of their observation run). Mask manufacturing and installation is only done at day time. Therefore the mask manufacturing has to be initiated 1 day before starting the observations. Only up to 10 masks can be stored in the magazine and observed in one night.

[2]The reason is alternating light traps which prevent sky light from falling between the slit blade carriers

MXU Slits: boundary conditions for the MXU slits are:

1. slit width: 0.″1 (minimum) to 40″
2. slit length: up to 40″
3. available field of view:
X: minus 15mm at either end; this is indicated by FIMS.
Y: full field of view
4. slit shapes: rectangular, circular, and curved slits.

Acquisition Accuracy: With the improved astrometry of FORS2 with the MIT CCDs the targets can be properly placed on the slits all over the unvignetted field of view in standard resolution mode.

Collimator Constraints: only observations with the SR collimator are supported.

Target Acquisition with MXU: The MXU mask design has to be prepared with FIMS. The alignment of the mask on the sky is done with user defined reference stars and with pre-defined reference slits on the bottom of the upper CCD.

2.4.8 Echelle Spectroscopy with FORS2 — ECH mode

Echelle Spectroscopy with FORS2: FORS2 allows Echelle spectroscopy in the blue spectral range. The Echelle grisms are located in the grism wheel, the cross disperser grisms in the Wollaston wheel. A cut-off filter is used to suppress the scattered infra-red light. The filter is placed in the converging beam below the camera.

Echelle	Crossdisperser	Orders	Wavel. range [nm]	Dispersion [Å/mm]/[Å/pixel]	RS	OSF
EGRIS_110B+98	XGRIS_600B+92	6 – 12	345 – 590	17 – 37/0.41 – 0.89	1530	FILT465

Table 2.7: Parameters of the Echelle grism and cross-disperser.

Transmission Characteristics: the Echelle efficiency curve for the blue grism is given in Figure C.4. The cross dispersers are optically identical to the standard grisms of the same name; the efficiency curve of the only cross disperser used so far is given in Figure C.4. The spectral format for the Echelle mode is shown in Figure 2.3.

Echelle Slits via MOS: the slit for this mode will be produced by the MOS slit 10, but can be extended by the adjacent MOS slit 9. The Echelle slit is placed in the MOS field center.

Target Acquisition for Echelle Spectroscopy: Only fast target acquisition mode is available for Echelle spectroscopy:

- the fast mode, where the object is identified by mouse click in an acquisition image followed by a telescope offset to put it into the MOS Echelle slit. This mode is suitable for brighter objects. Given the low efficiency of the Echelle grisms the fast mode may actually satisfy most observations in this mode.
- for faint sources the acquisition can be done with blind offsets in "fast" mode - the offsets will be executed after centering a reference star on the slit (template FORS1/2_ech_obs_mosSlit_fast).

Note: In almost all cases the same data can be obtained quicker with a long slit. For instance we advise the use of GRIS_600B in LSS mode with a slit width two times smaller (0.5"). A holographic grism (GRIS_1200B) will replace the Echelle mode in the near future.

2.4.9 Slitless Spectroscopy

Slitless spectroscopy can be performed in MOS mode with all slits open. Please not that the sky background will be the same as for imaging mode observations and jitter offsets between the exposures must be applied to achieve a good sky subtraction.

For the preparation of observations in slitless spectroscopy a very good understanding of the instrument optics is essential: Note that the 0th order of grisms 150I and 200I will fall into the field of view of FORS and contaminate 790 and

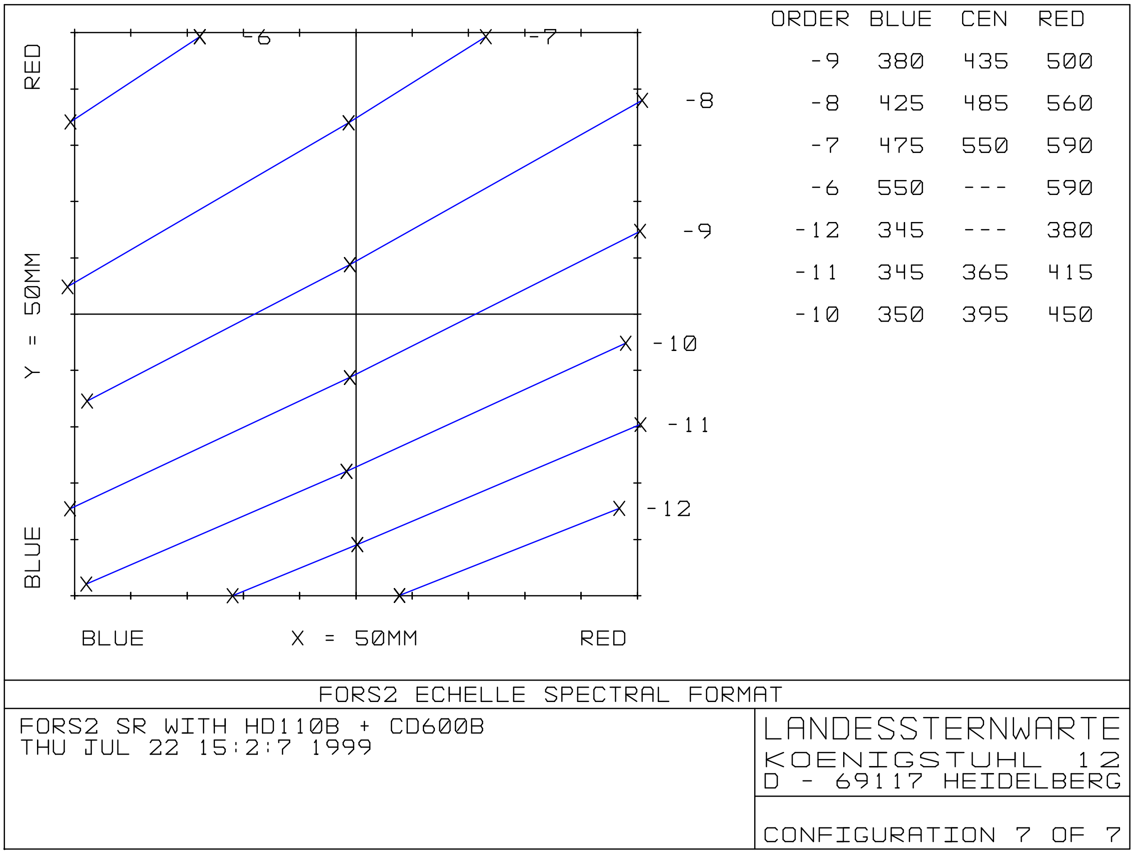

Figure 2.3: Spectral format of the EGRIS_110B+98 Echelle grism in FORS2. The plot shows the positions of the Echelle orders on the CCD, the corresponding wavelength range of each order is tabulated in the upper right corner of the figure.

300 pixels on the left/blue side of the field of view of FORS1 (24μm pixels) and 1260 and 480 unvignetted pixels of FORS2 (unbinned 15μm pixels). Any observation with filters of wavelengths which are off the central wavelength of the grism will cause field vignetting which can cut the field on both sides depending on the sign of the wavelength offset between filter and grism. Depending on the length of the spectra (the requested filter) the targets should be more than half the length of spectra off the zero order and the field vignetting!

2.5 Polarimetry with FORS1

Polarimetry Concept with FORS1: the polarimetric modes are implemented in FORS1 only. They allow the measurement of linear and circular polarization, both for direct imaging and spectroscopy. The polarization optics are located in the parallel beam section of FORS1 and consists of a Wollaston prism as beam splitting analyser and two superachromatic phase retarder plate mosaics (9 individual plates arranged in a square mosaic frame) to measure linear and circular polarization. Both mosaics are installed in rotatable mountings on a dedicated swing arm which can be moved in and out of the light path. The Wollaston prism is inserted in the uppermost wheel of the parallel beam section.

2.5.1 Imaging Polarimetry — IPOL mode

Strip Mask for Imaging Polarimetry IPOL: for imaging polarimetry (IPOL) of extended objects or crowded fields a strip mask is produced in the focal area of FORS1 to avoid overlapping of the two beams of polarized light on the CCD. When using the standard resolution collimator the strip mask is formed by placing every second MOS slit jaw carrier arm (odd numbered MOS slits) across the field of view of the instrument. A full coverage of the imaging field of view is then achieved by taking two frames displaced by 22″ in direction of the MOS slitlets. For the high resolution collimator a separate pre-manufactured strip mask of slits of 11" is moved into the focal area of FORS1.

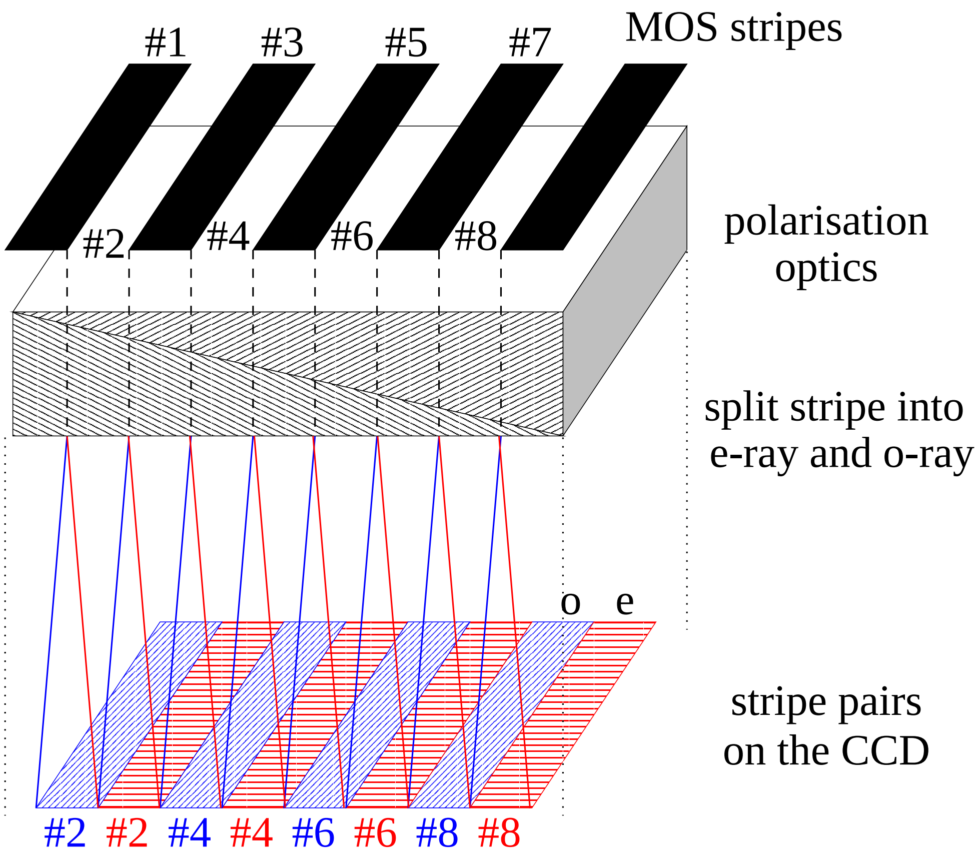

Figure 2.4: For imaging polarimetry (IPOL) of extended objects or crowded fields a strip mask is produced in the focal area of FORS1 to avoid overlapping of the two beams of polarized light on the CCD.

Field Coverage: since with IPOL observations only half of the full field of view of the FORS1 instrument is imaged on the CCD in one exposure, the complete field coverage can only be achieved by off setting the telescope accordingly in between exposures.

Retarder Plate Angles: the retarder plate angles can be selected from a set of fixed predefined angles (see Table 2.8).

Filters for IPOL: all imaging filters (see section B) can be used except the ones of the FORS1 instrument standard configuration (see section 2.2) which are located in the Wollaston wheel. The use of the latter ones is in principle possible, but requires a reconfiguration of the instrument. This, however, is considered for visitor mode observations

Retarder Plate	Position Angles (deg)
circular	**-45, 45**, 135, 225
linear	**0, 22.5, 45, 67.5**, 90, 112.5, 135, 157.5
	180, 202.5, 225, 247.5, 270, 292.5, 315, 337.5

Table 2.8: The table lists the angles of the predefined retarder plate positions which can be selected for imaging and spectropolarimetry with FORS1. To achieve the highest accuracy we are recommending to take exposures with the highlighted plate position angles.

only and needs a-priory approval by the observatory before proposal submission.

Target Acquisition in IPOL: Only Fast modes are available. In the fast mode the object is selected at the instrument console by mouse click in an acquisition image and the telescope is then offset such that the target is at the center field position of MOS slit 10. FIMS can still be used (PMOS mode with all slits open) to simulate the focal field geometry in cases of rather complex target distribution.

2.5.2 Spectropolarimetry — PMOS mode

MOS Slit/Strip Mask for Spectropolarimetry PMOS: spectropolarimetry (PMOS) using MOS slitlets is possible with the standard resolution collimator only. In this mode the MOS slitlet arms with odd numbers are positioned to form the same strip mask as for imaging polarimetry. The even numbered slitlets are available as in the normal MOS mode, i.e. they can be positioned on the objects in the field of view.

Slitless Spectropolarimetry: slitless spectropolarimetry can be implemented for SR collimator in a similar way as for MOS, but keeping the odd MOS slitlets in close position. It is also possible with the HR collimator using the special HR strip mask as for IPOL observations (fast acquisition mode only). See section 2.4.9 for general comments on slitless spectroscopy.

Grisms and Filters for PMOS: all grisms (but GRIS_600V+94) together with the recommended order separation filters can be used in PMOS mode. GRIS_600V+94 is configured for the Wollaston wheel and can't be mounted in the grism wheel. Other filters together with these grisms can be used if the filter is not mounted in the Wollaston wheel (see section 2.2).

Retarder Plate Angles: the retarder plate angles can be selected from a set of fixed predefined angles (see Table 2.8).

Collimator Constraints: spectropolarimetry PMOS is possible only with the SR collimator in FORS1.

Target Acquisition for PMOS: Fast and FIMS based acquisition modes are available but fast mode can only be applied for single target observations. Multi-object spectro-polarimetry will require mask preparation with FIMS. The fast mode will put the selected object on MOS slit 10 moved to the field center. The other MOS slits are set-up to the same position and slit width like slit 10 and can serve for sky background measurements. Blind offset acquisitions are supported.

2.5.3 Performance of the Polarimetric Modes of FORS1

The FORS1 polarization optics allow the determination of the degree of polarization to a relative error of $< 3\times10^{-4}$ and of the position angle (depending on the target polarization) to about 0.2°. For observation in the center of the field no instrumental polarization was found at the detection level of our measurement of $< 3\times10^{-4}$. For off-axes measurements (3 arminutes offset) spurious polarization of up to $\sim 8\times10^{-4}$ was detected in some measurements (circular polarization in this case).

Important update on the instrumental polarization: We have found a strong linear instrumental polarization in the corners of the field of view. This spurious polarization field shows a high degree of axial symmetry and smoothly increases from less than $3\text{x}10^{-4}$ on the optical axis to $7\text{x}10^{-3}$ at a distance of 3 arcmin from it (V band). In case of the other filters and spectro-polarimetric measurement there is no data available yet. The corrective functions can be estimated with an observation of a globular cluster with the respective filters. Such work is under way and you will find more information on the FORS webpage (`http://www.eso.org/instruments/fors/pola.html`).
Please note that there should be no problem for spectro-polarimetric observation of single targets in the center of the field of view or single targets in imaging polarimetry in the center of the field of view. In case of the circular polarization the spurious polarization was found an order of magnitude smaller.

2.6 High Time Resolution Modes

2.6.1 Overview

The principle of the high time resolution (HIT) mode is to move the charges in positive x-direction on the CCD while integrating the incoming light with the exposure shutter open. The time resolved spectra or light curves are stored on the CCD which is then read out at the end of the sequence with the mode of lowest read out noise (100kHz,2x2,high).

The HIT mode allows spectroscopic observation for a single target on a square aperture and imaging light curves of one or two stars on a long slit. For the spectroscopic mode the target is centered on an aperture on the extreme left side of the unvignetted field of view. This aperture is punched on pre-fabricated masks to be installed in the FORS2 mask exchange unit (MXU). There will be masks for various aperture sizes of up to 5 arcseconds. For the imaging modes the movable slit blades of the FORS MOS unit are used with all slits opened by a user specified slit width and placed to the extreme left side of the field of view. The position angle of the instrument can be selected such that a second target may be observed simultaneously. Please note that the HIT mode observations were only configured for the standard resolution collimator COLL_SR.

For the time being only one-shift modes are offered. One shift mode denotes that the charges are moved at constant speed on the detector until the complete detector is used as storage for the data. A part of the FORS2 MIT detector mosaic is vignetted by the FORS2 top unit. Therefore not all 4096 columns can be used to store the data, but only 3548 columns[3]. The charges are moved over this number of columns in the user specified times of 1s, 4s, 16s, 64s, 256s and 1024s. The resulting frequencies of 0.28 to 289 milliseconds are not the effective time resolution - the time resolutions is reduced by the seeing or the slit width in units of pixels. For an image scale of 0.125"/pxl and a seeing of 1" the time resolutions would be between 2.3 milliseconds and 2.3 seconds for the fastest and slowest modes.

HIT mode name	one-shift time	time resolution
HIT-OS1-1sec	1s	0.0023s/"
HIT-OS2-4sec	4s	
HIT-OS3-16sec	16s	
HIT-OS4-64sec	64s	
HIT-OS5-256sec	256s	
HIT-OS6-1024sec	1024s	2.3s/"

The readout mode 100kHz,2x2,high was selected to get the lowest possible readout noise level. All frames will be binned at the readout time. The CCD parameters like the binning are deeply hidden in the CCD configuration file and can not be changed during normal operation. About 40 seconds overhead time is expected to readout the full mosaic detector and to handle the data files.

The fundamental problem with the HIT modes is that even smallest image motions due to atmospheric effects or residual guiding offsets will strongly compromise the photometric accuracy of the measurements. Note that the respective targets will appear brighter while the residual image motion is in direction of the moving charges on the CCD. High accuracy photometry can not be done with the HIT modes unless a nearby star can be used as a reference source!

2.6.2 High Time Resolution Mode – Imaging (HITI)

The MOS slits will be placed to the extreme left side (-3 arcminutes) and opened to a user defined (typically broad) slit width. The mode (HITI) can be used with any available FORS2 filter of the FORS2 standard configuration and the exchangeable interference filters. Accurate photometry on a 1% level is only possible if there is a nearby star observed simultanously on the slit as a flux reference. Another requirement is to select a slitwidth which is larger then the actual seeing. The residual guiding offsets would reduce the performance to about the 10% level, without the differential measurement of a reference star. The atmospheric effects on the image motion would be only corrected in case of a reference star within the isoplanatic angle. This effect is however thought to be relatively small for large telescopes.

[3]This parameter is still to be optimized

2.6.3 High Time Resolution Mode – Spectroscopy (HITS)

The readout direction is for FORS2 in spectral direction for the standard FORS2 grisms. Only the cross-disperser grisms XGRIS_600B and XGRIS_300I can be used for the the HITS mode.[4] There are 7 masks available with slit widths between 0.5 and 5 arcseconds. The absolute photometric accuracy will be poor, since it is not possible to do a differential photometric measurements with a 2nd star on a slit. Equivalent widths of lines and for a wide slit also the colors should be less compromised by the image motion. Same as for the imaging mode: The slits are on the extreme left side of the field of view offset by about -3 arcminutes. The slits are little squares. The grism XGRIS_300I can be used with order separation filter OG590 or without. In the later case there would be some 2nd order overlap typically at the red end of the 1st order where the CCD response would be reduced The 2nd order overlap would start at >6600Å but would become important at wavelengths above about >8000Å depending on the color of the target. The following slit masks will be available:

mask name	slit width
HITS_0_5+900015	0.5”
HITS_0_7+900016	0.7”
HITS_1_0+900017	1.0”
HITS_1_3+900018	1.3”
HITS_1_6+900019	1.6”
HITS_2_0+900020	2.0”
HITS_5_0+900021	5.0”

The respective cross disperser grisms are either identical copies to the standard FORS2 grisms (600B, 300I) or are converted former standard grisms (600R). The wavelength range of the cross disperser grims are however slightly different from the standard grisms. This is primarily caused by the asymmetric mount of the FORS2 MIT CCD mosaic which is off-centered by 33”.

FORS2 cross disperser grisms for the HITS mode					
Grism	$\lambda_{\mathrm{central}}$ [Å]	λ_{range} [Å]	dispersion [Å/mm]/[Å/pixel]	$\lambda/\Delta\lambda$ at $\lambda_{\mathrm{central}}$	filter
XGRIS_600B+92	4452	3300 - 6012	50/0.75	780	
XGRIS_300I+91	8575	6000 - 11000	108/1.62	660	OG590+32
XGRIS_300I+91	8575	5032 - (6600)	108/1.62	660	
XGRIS_600R announced in earlier versions can not be used					

The central wavelength is defined as the wavelength $\lambda_{\mathrm{central}}$ in the center of the field of view. The gap between the two CCDs will cause a gap of about 7 pixels in the spectra at a wavelength of approximately $\lambda_{\mathrm{central}}$ - 267pxl * dispersion.

Visitor mode only! The cross disperser grisms are not included in the FORS2 standard configuration. There will be no instrument setup changes according to the service mode rules and accordingly the spectroscopic HITS mode is only offered in visitor mode! (HITI - imaging mode is offered both in visitor and service mode).

2.6.4 OB-preparation

The HIT mode templates for modes HITI and HITS are all of “fast mode target acquisition” type. There is no mask preparation required for the phase 2 observation block (OB) preparation. There are special templates available for the two modes: Three observations templates for the night time science observations for target acquisitions, through slit images and the science observation. Additionally flat field templates for HITI and HITS mode and an arc line spectral template for HITS mode.

For the HITI (imaging) mode the OB would consist of three templates in the following order:

FORS2_hiti_acq_fast	target acquisition
FORS2_hiti_obs_slit_fast	through slit image
FORS2_hiti_obs_exp_fast	science exposures

[4] Grism XGRIS_600R was announced in earlier versions of the document, but we have learned later that there are technical problems using this grism as cross disperser grism.

Very similarly in case of the HITS spectroscopic mode:

FORS2_hits_acq_fast	target acquisition
FORS2_hits_obs_slit_fast	through slit image
FORS2_hits_obs_exp_fast	science exposures

The detailed description of the template functionalities and parameters will be available in due time for the phase 2 proposal preparation.

2.6.5 Calibration plan

The bias frames of the normal spectroscopic modes can be also used for modes HITI and HITS. This is not the case for flats fields and arcs of cause. Please note that only the CCD columns are used to detect the incoming light onto which the slit or square aperture is projected. Pixel to pixel variations of the detector response can not be corrected. The flat field frames and arcs should not depend on the selected readout speed. The observatory staff will define an appropriate readout speed for which well exposed calibration frames can be achieved. For the other readout speeds it is typically impossible to get the exposure level right. Night time calibrations are not possible. Night time standard stars are to be selected by the HIT mode users and the respective observation blocks are to be prepared by the users.

2.6.6 Performance on the sky

The limiting magnitudes to reach a signal to noise ratio of $S/N = 5$ as obtained in every 2x2 binned pixels for the different grisms are given below. The value was calculated for the center of the wavelength range at dark time. The S/N would drop strongly in the blue part of grism 600B. For the spectroscopic mode the S/N is independent of the seeing for the very wide slit, but time resolution and spectral resolution would both become worse in case of a bad seeing. Here for the slowest readout mode of 1024 seconds per one-shift:

grism	limiting magnitude
XGRIS_600B	15.8
XGRIS_300I	15.9

The expected number of counts per binned pixels can be derived by the following equation for a 10th magnitude star[5], a dispersion of 0.75 Å/ pxl, response ~ 0.17, 0.75 Å/pxl and an OS-time of 256s:

$$\begin{aligned} \text{counts} &= \text{flux} * \pi * R^2 * \text{resp} * \text{disp} * \frac{\text{time}}{3548} * \text{bin}^2 && (2.1)\\ &= 1000 * 10^{-0.4*10} * \pi * 405^2 * 0.17 * 0.75 * 0.00028 * 256 * 2^2 && (2.2)\\ &= 1757 \text{ photons} && (2.3) \end{aligned}$$

In case of the imaging modes the number of parameters like seeing, night sky brightness,. . . and the number of filters is very high and it's hard to present a meaningful table with limiting magnitudes here. The expected count rates integrated in spatial direction (no slit losses) for a filter width of 1115Å are estimated by the following equation for a 15th magnitude star:

$$\begin{aligned} \text{counts} &= \text{flux} * \pi * R^2 * \text{resp} * \text{fwhm} * \frac{\text{time}}{3548} * \text{bin} && (2.4)\\ &= 1000 * 10^{-0.4*15} * \pi * 405^2 * 0.3 * 1115 * 0.00028 * 256 * 2 && (2.5)\\ &= 17288 \text{ photons} && (2.6) \end{aligned}$$

You may have to distribute the 17000 photons over the PSF and to devide with the gain factor of 0.7e^-/adu to estimate peak flux values and the integrated signal to noise ratio.

[5] $1000 * 10^{-0.4*10}$ photons $* \text{cm}^{-2}\text{Å}^{-1}\text{s}^{-1}$ at 5500Å - the 1000 photons at 5500Å for a 0th magnitude star is just a nice number to remember.

2.7 Rapid Response Mode for FORS

Starting in Period 74, a new mode, the Rapid Response Mode (RRM), is offered for observations of transient phenomena such as gamma-ray bursts or supernovae in semi-automatic mode. The user (PI or Co-I of an approved target-of-opportunity program) submits an ftp file with the coordinates of the target to a specific ftp server on Paranal. A special program at the telescope continuously monitors this ftp directory; when it detects a file, it checks if the filename corresponds to an approved activation code, and if this is the case, the on-going observations are ended, and a new BOB starts an OB with the same name as the ftp file. The telescope automatically presets to the coordinates specified in the ftp file, and the requested observations are performed straight away.

PIs of approved FORS ToO programs requesting this mode need to prepare their OBs in the usual way. However, these RRM programs use specific acquisition templates described in the FORS Template Reference Guide. More information on the RRM can be found on the USG Phase II webpages (`http://www.eso.org/observing/p2pp/rrm.html`).

2.8 Detectors

2.8.1 General Properties

Chip Characteristics, Pixel Number and Size, CCD Control: the FORS1 detector is a 2048×2048 Tektronix CCD, thinned and anti-reflection coated. The pixel size is 24 × 24 μm. The surface of the curved CCD can be fitted with a sphere of a radius of 2300 mm (FORS1). The curvature is taken into account by the camera field lens. The new detector mosaic of FORS2 consists of two 2k×4k MIT CCDs, thinned and anti-reflection coated. The detectors are flat and the bottom detector is rotated by 0.08 degree and shifted by 30μm with respect to the upper "master" detector. The gap between the two detectors is 480μm The CCDs are controlled by FIERA controllers. The detector systems are not interchangeable between both instruments.

Read-out Modes: the FORS1 CCD can be read in single (port A) and four-port read-out mode with amplifier ports ABCD, the four ports are located at the corners of the chips. Two ADU level settings are implemented: high and low. Three pixel binnings are possible: 1x1, 2x2, 4x4. The allowed combinations of read-out ports, ADU level settings and pixel binnings are listed in Table 2.9. The CCD is read with a speed of 50kHz. In case of FORS2 only the 2-port readout is supported for the MIT CCDs. The default readout modes will be 200kHz,2x2,low for imaging (2x2 binned, low gain mode read with 200kHz), 100kHz,2x2,high for spectroscopy. For special applications such as high resolution imaging or deconvolution techniques an unbinned mode is supported: 200kHz,1x1,low.

Read-out Port	gain	Binning	comment
FORS1: default modes			
ABCD	high	1x1	imaging
A	high	1x1	spectroscopic
FORS1: other modes			
ABCD	high	2x2	
A	high	2x2	
ABCD	high	4x4	
ABCD	low	1x1	
A	low	1x1	
ABCD	low	2x2	
A	low	2x2	
ABCD	low	4x4	
A	low	4x4	
FORS2: default modes			
200kHz,2x2,low			imaging
100kHz,2x2,high			spectroscopy
FORS2: other modes			
200kHz,1x1,low			high resolution

Table 2.9: Detector set-ups of FORS for normal CCD modes

Standard Operation Modes of the CCDs: only the following standard CCD set-ups are offered for service mode observations:

- ABCD,1x1,high — FORS1: direct imaging IMG, OCC and imaging polarimetry IPOL
- A,1x1,high — FORS1: spectroscopy LSS, MOS, PMOS
- 200kHz,2x2,low — FORS2: direct imaging IMG, OCC
- 100kHz,2x2,high — FORS2: spectroscopy LSS, MOS, MXU, ECH

Visitor mode observations allow the full complement of CCD read-outs. However, it is strongly recommended to use the CCD standard operations read-out modes whenever possible (for instance to benefit from the calibration data taken in the context of the FORS instrument calibration plan).

Noise, Gain and Conversion Factors: the read-out noise (RON) and conversion factors (K) as measured on the site for all CCDs are given in Tables 2.10. Please note that low gain denotes high charge conversion factors K (in e^-/adu) and

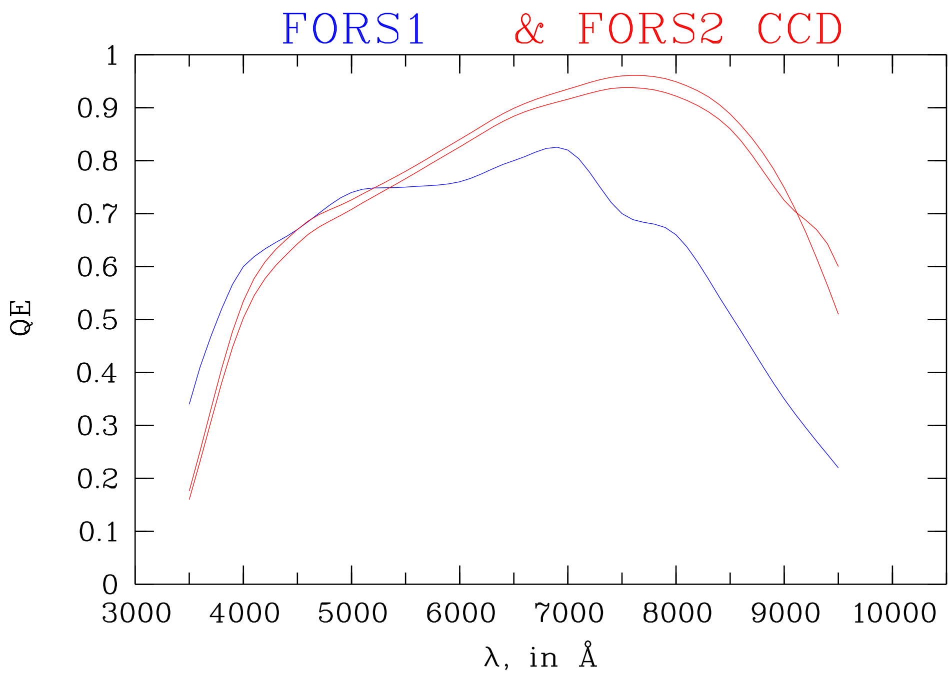

Figure 2.5: Quantum efficiency of the FORS CCDs (Tektronix and the two MITs).

slightly higher readout noise. Pickup noise is clearly visible for the fast imaging modes and in some exposures of the slow spectroscopic mode with the MIT CCDs of FORS2.

Linearity, Full Well Capacity, Dark Current etc.: some more characteristic data of the CCDs are given in Table 2.11. None of the CCDs will saturate before reaching the numerical truncation limits (65535adu).

Read-out Speed and Times: detector readout speed is 50 kHz for the Tektronix and Site detectors but 100 kHz and 200 kHz for the spectroscopic and imaging modes with the MIT mosaic detectors. Approximate readout times for various modes are given in Table 2.12. Please note also that window readout is possible only in single-port readout through port A of FORS1 and only for FORS1! In window readout mode the typical readout time will depend on the position and size of the window. For simplicity the readout time including all overheads should be estimated by the following equation: 30s + 92s * (DET.WIN1.NX * DET.WIN1.NY) / (2080*2048) - with the size of the window NX and NY as specified by the users.

CCD Defects: at a number of positions on the FORS Site and Tektronix CCDs the efficiency is significantly reduced. Although the effect is linear and can be corrected by flat-fielding the data, it should be avoided to place the science target onto these spots with quantum efficiencies below the expected level. The typical size of the spots is about 5 pixels, but some spots are much larger as summarized in Tables **??** for FORS1. Note that in the tables the deficit flux is given for the worst pixel only. Vertical "bleeding" of the CCD occurs for overexposure levels beyond 5 times saturation level. Horizontal charge memory effects over a few pixels are seen for extremely bright sources. Cross talks in 4-port read-out is detected to be of the order of 0.01 percent between ports C and D, by a factor of 4 less between D and C and negligible between ports A and B. Bad columns are occasionally seen at X = 1357 for the FORS1 CCD and at X = 1226–1228 for the old FORS2 Site CCD.

2.8.2 Fringes

Tektronix and SITE CCDs: The fringe amplitudes of the FORS detectors are relatively low and only observed at wavelength greater ~750nm.

MIT mosaic detector: The amplitudes of the internal CCD fringes are strongly reduced in respect to the Site and Tektronix CCDs. For Bessel I imaging fringes are hardly visible (circular fringes from the filters are however visible for I_BESS and R_SPECIAL filters). For z_Gunn imaging the fringe amplitudes are below 1% and in the strongest telluric

		FORS1		old SITE CCD FORS2	
port	gain	RON [e^-]	K [e^-/ADU]	RON [e^-]	K [e^-/ADU]
A	high	6.25±0.06	1.28±0.01	5.2±0.1	1.85±0.03
B	high	6.90±0.09	1.60±0.01	5.5±0.1	2.00±0.02
C	high	6.70±0.09	1.44±0.02	5.3±0.1	1.90±0.02
D	high	6.96±0.16	1.41±0.03	5.5±0.1	1.83±0.05
A	low	7.21±0.08	3.51±0.04	5.6±0.1	2.62±0.03
B	low	8.07±0.06	4.36±0.03	5.9±0.1	2.81±0.05
C	low	7.69±0.06	3.89±0.03	5.8±0.1	2.68±0.04
D	low	7.78±0.16	4.09±0.06	5.7±0.1	2.61±0.03
				new MIT CCDs FORS2	
master	low, 200kHz			4.1	1.25
slave	low, 200kHz			4.2	1.25
master	high, 100kHz			2.7	0.70
slave	high, 100kHz			3.0	0.70

Table 2.10: Detector readout noise and conversion factors. Port A of FORS1 is the lower left, B the lower right, C the upper left and D the upper right quadrant.

Parameter	FORS1	FORS2 - SITE	FORS2 - MIT
photosensitive pixels (HxV)	2048×2048	2048×2048	2*4096*2048
pixel size (μm)	24	24	15
dark current at –120C (e^-/px/h)	8	15 - 25	~ 3
linearity (up to full well; % RMS)	< 0.4	< 0.5	
cosmic ray rate (events/min/cm^2)	3.4 ± 0.2	2.4 ± 0.3	

Table 2.11: Basic characteristics of the FORS CCDs. H = horizontal, V = vertical.

lines in spectroscopic modes fringe amplitudes were found to be of the order of 5% in the worst cases.

Jitter and nodding on the slit: It will be mandatory to use offset techniques (jitter images, nodding on the slit) to subtract the sky background at wavelengths greater ~800nm for spectroscopy and due to the detector cosmetics at any wavelength in imaging mode. The fringes are quite stable but depend on the spectrum of the night sky which will be variable. To subtract a scaled master sky will give quite reasonable results even at z-band wavelengths where observations without jitter or nodding will be very hard to calibrate. Most applicants will observe fainter targets with 8m-class telescopes while the sky will be as bright as with any other telescope.

2.8.3 Shutter

FORS contains a rotating half-segment exposure shutter which guarantees uniform illumination of the CCD to the 1 % level or better for exposure times as short as 1 sec (the shortest possible exposure time is 0.25 sec).

2.8.4 CCD Contamination

The CCD dewars of both FORS1 and FORS2 showed contamination effects from the very beginning of science operations with the instruments. The contamination affects mostly the relative sensitivity across the CCD, i.e. it changes toward the edges and appears as a diffuse quadrangle in the outer part of the chip. The contamination is most pronounced in the UV wavelength region and it is growing over time. It can be cured (i.e. removed) by a special warm-up procedure (currently done every ~ 6 months).

A major CCD dewar maintenance in October 1999 considerably improved the contamination of FORS1, but did not remove it completely. The FORS2 deward was also contaminated and a similar maintenance of the dewar was exercised in January 2000. The measurements of the CCD contamination indicate that the growth rate of the contamination slows down with each decontamination cycle of the dewar. The impact on the scientific applications will be minor since the effect on photon response is very small and the typical time scales of the growth of the contamination pattern is now of the order of months.

readout area	speed, binning	port	readout time	default mode for:
FORS1 Tektronix				
2k×2k	50kHz,1x1	A	122s	spectroscopy
2k×2k	50kHz,1x1	ABCD	51s	imaging
2k×2k	50kHz,2x2	ABCD	25s	
window (100×100)	50kHz,1x1	A	undefined!	
FORS2 MIT mosaic				
2×4k×2k	100kHz,2x2	2-port	41s	spectroscopy
2×4k×2k	200kHz,2x2	2-port	31s	imaging
2×4k×2k	200kHz,1x1	2-port	62s	

Table 2.12: Approximate CCD readout times in the different read-modes. The read-out times include the overheads during the exposure execution (for CCD wiping, header compilation).

The new MIT mosaic detectors of FORS2 are clean!

2.9 The Calibration Units

Each FORS instrument contains two sets of internal calibration lamp units in its top section. The light from a variety of calibration lamps is projected onto a calibration screen inside the telescope, located approximately 2.5m above the instrument. All lamps can be switched on and off individually and in several combinations by means of calibration templates (see FORS1+2 Template Manual). Blue and red flat field lamps as well as Neon and Argon arc lamps are installed in both calibration units. He and HgCd arc lamps are only installed in one of the two calibration units. A guide to approximate exposure times is given in sections 4.4 and 4.5, a spectral atlas of the FORS spectral calibration lamps in appendix D. The red internal flat field lamps can't be used anymore after the installation of the external calibration units. The control electronics of the respective lamps is now used by the external units.

External Calibration Units: the flatfield lamps in the old internal calibration units have produced parasitic light in MOS and LSS flatfield exposures (see section 2.9.1). Therefore, new external calibration units (ECUs) have been installed which are located above the LADC in the Cassegrain tower. The new calibration units consist of two blue and two red lamp which are linked to the Cassegrain tower with a fiber bundle. One of each red and blue lamps will be projected into the fiber bundle in focus (high illumination level) while the other lamps are out of focus of the projection optics. Only one of the two red and one of the blue lamps can be used at a given time. The ECUs are the only calibration units used for spectroscopic flats fields since March 2003 for FORS1 and April 2003 for FORS2, respectively. Actually we use the faint red lamp together with the bright blue lamp such that there is a secondary peak in the flat field spectrum which may appear odd on the first view. Since the data reduction requires to normalize the flat fields anyway there should be no negative consequences from the little bump, but far more light in the blue,. . .

Nighttime Calibrations: For technical reasons the arcs and flats are only taken at day time with the telescope, guide probe, LADC parked and the beam shutter (identical with the calibration screen) closed.

2.9.1 Parasitic Light in Longslit and MOS/PMOS Flatfields

As a reference for the data reduction of older data taken with the internal calibration units we still want to provide the following informations:

Longslit Mask: due to multiple scattering in the longslit mask, parasitic light from the flatfield lamps of the instrument has reached the CCD detector. This light appeared as high spatial frequency horizontal wave or ripple pattern in the flatfield exposures. The position on the chip varied with the use of the calibration unit.

MOS/PMOS Set-ups: due to multiple reflections of light from the calibration lamps at the LADC and the side walls of the MOS slit carriers, flatfield exposures have shown a few higher exposed pixel rows at the upper or lower edge of the slit image on the CCD (depending on the calibration unit used for the exposures).

Two sets of flatfields using alternatively the lamps of only one calibration unit were taken in order to compute a clean flatfield with the parasitic light partly removed from the calibration flatfield. For the wavelength calibrations the parasitic light is of little to no concern.

2.10 Forthcoming New Equipment and Observing Modes

GRIS_1200B to replace the Echelle mode: The Echelle mode with the two conventional grisms is known to perform bad in terms of it's instrument response. We are planning to order a volume phased holographic grism to be used on FORS1 which should provide at least a factor of 3 more response then the Echelle mode of FORS2 or the respective 2nd order observations which also show relatively low performance. The respective wavelength range would be 3730 to 4970 Å with the central wavelength at 4340Å a dispersion of 0.61 Å/ pxl and a spectral resolution of 1430 for a slit width of 1 arc-second.

2.11 'Retired' Instrument Components

Table 2.13 lists the instrument components which are no longer offered for FORS and the time period during which they were used.

Removed Component	Used in	Availability	Reason for Removal	Replacement
H_Alpha+59	FORS1+2	1/4/99-30/9/00	ghosts	H_Alpha+83
GRIS_600z+16	FORS1	1/4/00-31/3/01	low response	GRIS_600z+26
GRIS_600R+24	FORS2	1/4/00-31/3/02	low response	GRIS_600RI+19
XGRIS_600V+90	FORS2		no red Echelle	none
XGRIS_300I+91	FORS2		no red Echelle	none
2k×2k Site CCD	FORS2	1/4/00-31/3/02	red optimization	MIT mosaic
GRIS_600z+26	FORS1+2	1/4/00-31/9/02	low response	none

Table 2.13: "Retired" instrument components

Chapter 3

Observing with FORS

All observations with FORS are done via "observing blocks" (OBs). OBs contain of the target information and a small number of users selected "observing templates" depending on the observing mode. The users will fill out the parameter fields ("keywords") of the templates (eg. grisms, filters, slits). All the preparations are done with the phase 2 proposal preparation tool p2pp. Furthermore FORS masks will have to be prepared with the FORS instrument mask simulator "FIMS". The detailed information for the observation preparation are given in the p2pp-manual, the FORS template manual and the FIMS-manual. The instructions how to retrieve the manuals from the WEB pages are given in Section 1.

The strategy behind (observing blocks and templates) is to prepare the observations well in advance to minimize any interactive steps during the observations (optimization and service mode compatibility). The execution of the OBs will be mostly automatic and the execution will be done by telescope and instrument operators or the staff astronomers. Direct interaction at execution time is needed only for the target identification and the quality control of the data or for real time decisions. In the following we summarize the steps from a successful application to the final access of the data.

The preparation of service mode observations will require special care, some more rules and recommendations, since unclear points in the service mode packages will significantly delay the execution of the project. The additional requirements and instructions for service mode observations are available on WEB pages:

http://www.eso.org/observing/p2pp/
http://www.eso.org/observing/p2pp/ServiceMode.html

3.1 Selecting the Observing Mode

The first step is to select the best observing mode according to the scientific needs. In some cases there will be a choice between eg. MOS and MXU mode for example to observe 10 targets well distributed over the FORS field of view and in this case the optimization of the strategy will start at this point. In most cases the observing modes will be pre-defined and only a limited number of observing templates are needed and have to be studied with the help of the FORS template manual in detail.

3.2 Fast modes or FIMS mask preparation

All multi-object observations in modes MOS, MXU and PMOS will require the preparation of mask with FIMS. Occulting bar imaging and slitless spectroscopy is only supported with fims-based modes. Typically the mask design has to be ready before starting the preparation of the observing blocks.

Meanwhile all observations in modes IMG, IPOL, LSS and ECH are done without using FIMS - as well as single target observations in "PMOS" mode. For faint targets we support blind offset acquisition modes for all the fast modes (this is done with the through slit templates). The astrometric requirements are similar for blind fast acquisitions and FIMS acquisitions. In general the OB execution in fast mode won't be much faster than the FIMS mode, but the OB preparation will be.

3.3 Selecting the Instrument Setups and Exposure Times

A good understanding of the instrument is required, before starting the preparation of the observing blocks. It is possible to define observing sequences which don't make any sense - both within FIMS and within p2pp. Inconsistencies should be eliminated by the user, although a cross check of the OBs will be done both in visitor and service mode by verification scripts or the staff astronomers. It will be one of the first steps to define the instrument setups (chapter 2) and to calculate the exposure times with the exposure time calculator.

3.4 OB-preparation — FIMS based modes

1. Get your pre-imaging data or other astrometrically corrected images (see section 2.4.2)
2. Select the observing mode, the instrument setup and calculate the exposure times with the exposure time calculator
3. Prepare your masks with FIMS and keep the fims output file with suffix `.fims` to reload the mask if needed and the output files with extensions `.p_targ`, `.p_focf` (and `.p_gbr` for MXU mode) for the OB preparation. These files will be saved by FIMS in directory `~/.fims/SET/`
4. Make a hard-copy of the mask configuration within FIMS on which the reference stars and slits are well visible and a few hard-copies of the same masks with high magnification. This will be the typical set of finding charts needed at the end
5. Prepare the observing blocks - a typical OB in imaging mode (with occulting bars "OCC mode") will consist of two templates:

FORS_img_acq_align	target acquisition
FORS_img_occ_crsplit	science exposure

or similar for imaging polarimetry:

FORS_ipol_acq	target acquisition
FORS_ipol_obs_off	science exposures

For all spectroscopic modes a through slit image is required to verify the proper centering of the target on the slit. For observing modes MOS, MXU, LSS or PMOS the OB would typically consist of the following three templates:

FORS_mos_acq	target acquisition
FORS_mos_obs_slit	through slit image
FORS_mos_obs_off	science exposures

here the MOS mode as an example but with an identical sequence of observing templates for the other spectroscopic modes.

In case you want special calibrations not included in the FORS calibration plan (section 4.1) a calibration OB has to be prepared which would look like the following scheme (again for the MOS mode example):

FORS_ima_cal_coll	collimator selection
FORS_mos_cal_scrflat	screen flats
FORS_mos_cal_wave	screen arcs

where the first template is only used to select the collimator.

There are a few important points to be verified now:

(a) don't mix observing modes in one OB

(b) make sure that all fims input files belong to the same mask - in general only one mask per OB is possible: The keyword INS.FIMS.NAME on the top of the p_focf, p_targ and p_gbr files must be identical.

(c) be sure that the requirement for reference stars (and reference slits in MXU mode) are fulfilled - the details about the reference star selection are explained in the fims manual

3.5 OB-preparation — Fast modes

1. Get any imaging data and good target coordinates and very good astrometry in case of blind offset acquisitions (see section 2.4.2) and prepare finding charts with targets, slit positions and reference stars for blind offset acquisitions
2. Select the observing mode, the instrument setup and calculate the exposure times with the exposure time calculator
3. Prepare the observing blocks - a typical OB in imaging mode (fast "IMG mode") will consist of two templates:

FORS_img_acq	target acquisition
FORS_img_obs_crsplit	science exposure

or similar for imaging polarimetry:

FORS_ipol_acq_fast	target acquisition
FORS_ipol_obs_off_fast	science exposures

For all spectroscopic modes a through slit image is required to verify the proper position of the target on the slit. For fast observing modes LSS, ECH, SPECPHOT or PMOS the OB would typically consist of the following three template:

FORS_lss_acq_fast	target acquisition
FORS_lss_obs_slit_fast	through slit image
FORS_lss_obs_off_fast	science exposures

here for the LSS mode but very similarly for the other spectroscopic modes. For blind acquisitions in "fast" modes LSS, ECH and PMOS the coordinates of the reference star will be required for the target acquisition. The offset from the reference star to the target will be executed from the through slit image template, after fine adjustment of the reference star on the slit.

In case that you ask for special calibrations not included in the FORS calibration plan (section 4.1) a calibration OB has to be prepared which would look like the following scheme:

FORS_ima_cal_coll	collimator selection
FORS_lss_cal_scrflat_fast	screen flats
FORS_lss_cal_wave_fast	screen arcs

where the first template is only used to select the collimator.

There are a few important points to be verified now:

(a) don't mix observing modes in one OB

(b) make sure that the same slits are used in LSS mode for all templates within an OB

(c) verify that the offsets for blind offset acquisitions are correct in size and sign

3.6 Estimate execution time and optimize overheads

In the following example in MOS mode we presumed that the reference stars for the target acquisition were bright enough to be seen in 5 seconds (fims mode or blind acquisition typically with broad band filters) and that there were some targets on the slits which can be seen in 60s on the through slit image which is ideally done without filters in case of FORS1 (atmospheric dispersion corrector!) or with a broad band filter in case of FORS2 (to reduce the sky brightness in case of the IR sensitive MIT detector). No further acquisition overheads are required for the imaging mode after the preset and the start of the active optics correction. There is in most cases no need to repeat the acquisition procedure in the spectroscopic modes. The through slit images taken with the targets on the slits typically have to be repeated in case of corrections of the order of 1 pixels. Two loops are require to verify safely that the targets are on the slits.

Telescope	
telescope preset	3 min
guide star acquisition	0.75 min
active optics	2 min
LADC resetting	1 min
Interactive Acquisition (excluding exposure time)	
one loop IMG(occulting)/IPOL	1.5 min per loop
one loop MOS/MXU/PMOS	2.0 min per loop
one loop LSS/ECH/HIT	1.5 min per loop
two loops through-slit exposure	2.0 min per loop
Instrument	
instrument setup	0.5 min
collimator exchange	4.5 min
retarder plate setup	1.0 min
Exposure	
integration time	user defined
FORS1 read-out A,1x1,high	122s
FORS1 read-out ABCD,1x1,high	49s
FORS1 read-out ABCD,2x2,high	25s
FORS2 read-out 100kHz binned	41s
FORS2 read-out 200kHz binned	31s
FORS2 read-out 200kHz unbinned	62s

Table 3.1: Operational overheads with FORS on the VLT. The through-slit exposure is typically executed twice. It is important to include the overhead times while preparing proposals and service mode observations packages.

FORS1_mos_acq	
telescope preset	180s
guide star acquisition	45s
active optics (2 loops)	120s
acq. image integration time	5s
acquisition procedure	120s
FORS_mos_obs_slit – 2 loops!	
instrument setup	30s
through slit integration time (2*60s)	120s
through slit image (2*120s)	240s
FORS_mos_obs_off – NEXP = 1 & NOFF = 1	
instrument setup	30s
science integration (1*3000s)	3000s
1-port CCD readout (1*122s)	122s
all OB execution time	4012s

FORS2_mos_acq	
telescope preset	180s
guide star acquisition	45s
active optics (2 loops)	120s
acq. image integration time	5s
acquisition procedure	120s
FORS_mos_obs_slit – 2 loops!	
instrument setup	30s
through slit integration time (2*60s)	120s
through slit image (2*120s)	240s
FORS_mos_obs_off – NEXP = 1 & NOFF = 1	
instrument setup	30s
science integration (1*3000s)	3000s
100kHz,2x2 CCD readout (1*41s)	41s
all OB execution time	3931s

FORS1_img_acq	
telescope preset	180s
guide star acquisition	45s
active optics (2 loops)	120s
FORS_img_obs_crsplit – NEXP = 1 & NOFF = 5	
instrument setup	30s
science integration (5*600s)	3000s
4-port CCD readout (5*49s)	245s
all OB execution time	3620s

FORS2_img_acq	
telescope preset	180s
guide star acquisition	45s
active optics (2 loops)	120s
FORS_img_obs_crsplit – NEXP = 1 & NOFF = 5	
instrument setup	30s
science integration (5*600s)	3000s
200kHz,2x2 CCD readout (5*31s)	155s
all OB execution time	3530s

There would be an additional overhead of 270 seconds to exchange the collimators but this setup is partly executed during the telescope preset and the guide star and active optics setup procedure. Further overheads of 60 seconds per template exist for the PMOS and IPOL science templates to setup the retarder plates. This is now the time to optimize the strategy and to estimate if all your OBs can be done in the limited number of nights or service mode hours!

3.7 Visitor Mode

3.7.1 The final package

The final package needed at the telescope will typically consist of:

- finding charts
- observing blocks
- the fims output files and the pre-imaging data on which the fims preparation was done (fims modes)

In most cases the meteorological conditions will be fine, but there are also bad nights with bad seeing or clouds and sometimes strong wind which will come typically from the North.

3.7.2 At the telescope

The telescope and instrument operation is done by the staff personal. A good finding chart and a close collaboration between staff and visiting astronomer is the fastest way to the slit. The incoming data will be displayed on real time displays which will allow only very basic assessment of the data and automatically transferred to an offline workstation with data reduction software packages (iraf, Midas and idl). The basic observing modes will be pipeline reduced but sky subtraction and target extraction has to be done interactively. The working environment is described on the Science Operation WEB page: http://www.eso.org/paranal/sciops/. At the end of the night an automatic procedure calobBuilt will be started which will create a complete calibration OB for all modes and setups used during the night. The calibration OB will be executed during the morning hours.

3.7.3 At the very end

Finally after the last night a package of all science, calibration and test data is prepared by the data handling administrators optionally on CD-ROM, DVD or DAT and only one copy. Reduced data (no matter if pipeline or interactive reduction) are not on the package but DAT tapes are available to help yourself.
Please send us your end of mission reports with evaluations and suggestions – available from WEB page:

`http://www.eso.org/paranal/sciops/`

3.8 FORS and the Unit Telescopes

3.8.1 Guide Stars, Telescope Offsets

All FORS science observations will require a guide star in the unvignetted field of view of the Unit Telescope. The guide star is used for the alignment of the telescope relative to the guide star coordinates, for the wave front sensor of the active optics system and for fast off-axis guiding with typical tip-tilt corrections of the M2 of greater than 20Hz.

The guide stars are automatically found from the USNO catalog by the telescope control system (TCS) during the acquisition of the field. Due to the limits of the Cassegrain field of view and vignetting constraints for the FORS instruments the optimum distance range for guide stars from the field center is 4 – 7.4 arcmin for the SR collimator and 2 – 7.4 arcmin for the HR collimator. Depending on the seeing the guide star brightness should be between 10 – 13 mag.

For small telescope offsets (a few arcsec to a few arcmin), the telescope may keep the same guide star; otherwise it will automatically try to find a new one. Whether or not such telescope offsets cause a change of the guide star, depends on the offset amplitude and direction and on the position of the original guide star in the field. If the guide star is kept during an offset, the offset accuracy will be better than 0.1 arcsec. If the guide star is changed, larger offset errors can be introduced by the uncertainties of the guide star positions.

3.8.2 Telescope and Instrument Focus

The telescope focus is automatically set by the active optics system. No intervention is required by the observer. Defocussing of the telescope is not possible during the observations. The instrument focus is corrected automatically for the different thickness of the various filters, for the grisms, collimator and for varying instrument temperature (autofocus). For user-provided filters (visitor mode only) the instrument focus will be determined by the observatory engineering and operations staff which requires the provision of these filters to the observatory at least 6 weeks before the scheduled observing run.

3.8.3 Instrument Rotation and Position Angle on the Sky

FORS can be rotated independently from the guide probe. The allowed range for rotator presets with FORS is -180 to +180 deg while the operational range with FORS is -270 to +270 deg. Please note that the rotator offset angle of the telescope is minus the position angle of the targets on the sky. Note that a value of “9999” can be used to set the position angle to the parallactic angle.

3.8.4 Atmospheric Dispersion Compensation

Atmospheric dispersion is partially compensated by a linear atmospheric dispersion compensator (LADC) which is built into the M1 cell of the telescope in front of the Cassegrain focus.[1] It is designed to maintain the intrinsic image quality of FORS for zenith distances between 0 and 45° and to significantly reduce the effects of the atmospheric dispersion at higher airmass. The LADC position is automatically set when the telescope is preset to the target position and can not be corrected during the exposure. It is recommended to reset the LADC after significant changes in airmass during long series of exposures. At zenith distance larger then 45 degree the LADC prisms remain however always at the maximum separation. Although placed in front of the polarization optics there are no negative impacts (instrumental polarization) for polarimetric measurements expected or known.

[1] The LADC is described in G. Avila, G. Rupprecht, J. Beckers: Atmospheric Dispersion Correction for the FORS Focal Reducers at the ESO VLT, “Optical Telescopes of Today and Tomorrow”, A. Ardeberg (ed.), Proc. SPIE 2871, 1135 (1997)

Chapter 4

Calibrating and Reducing FORS Data

4.1 Calibration Plan

The VLT observatory aims at providing calibrations of the FORS instruments with an accuracy as listed in Table 4.1. Applicants have to request additional observation time including overheads if much higher accuracy is required than given below or if the mode is not supported by the calibration plan. In this case the respective observation blocks must be provided by the users.

The FORS Calibration Plan will ensure that ESO provides dark frames, biases, flat field frames and arc lamp spectra with the exceptions given below. Observations of standard stars in broad band filters are executed to obtain photometric zero points, atmospheric extinction coeficients and first order color terms for the UBVRI filters. For the other filters only one flux standard star close to airmass 1 is taken. Spectra of spectro-photometric standard stars with 5 arcsec slit width will provide response functions for the flux calibration of spectroscopic data. The standards for the spectroscopic modes are all observed with the MOS slits in the center of the field to avoid additional target acquisition overheads. Neither the longslits nor the MOS or MXU slits of the science setups are in the center of the field of view. Therefore some part of the spectra won't overlap with the derived response function. Please request special calibrations (send OBs) if this is problematic for your scientific data reduction.

Visitor mode observers are welcome to use calibration data taken in the framework of the FORS Calibration Plan. They should expect about half an hour per night to be used by observatory staff for calibration exposures. In most case the staff will observe one field with photometric standards for the performance monitoring and a spectro-photometric standard with a 5 arcsecs MOS slit for the setups used in the respective nights.

The calibration plan does not support:

1. night time standard stars and twilight flats for non standard CCD-modes — as a baseline only the CCD read-out modes ABCD,1x1,high (imaging), A,1x1,high (spectroscopy) for FORS1 and 200kHz,2x2,low (imaging), 100kHz,2x2,high (spectroscopy) for FORS2 will be supported.
2. any standard star observations to correct for telluric absorption lines
3. radial velocity standards
4. spectro-photometric standards for 2nd order spectroscopy with FILT_465_250
5. any day or night calibrations for slitless spectroscopy
6. any day or night calibrations for spectroscopy with filters other then the recommended order separation filters GG375, GG435, OG590 and FILT_465_250
7. any day or night time polarimetric calibrations for retarder plate angles different from 0,22.5,45,67.5 degree (linear) and -45,45 degree (circular polarimetry)
8. any PMOS screen flats at retarder plate angles different from 45.0 degree
9. any IPOL screen flats

Calibration Mode	Collimator	Frequency (4)	Number	Time	Results	Accuracy
Bias		weekly	5	Day	bias level, RON	RON/2
Darks		monthly	3	Day	dark current	
Screen Flats UBVRI	SR	weekly	2	Day	CCD check	
Astrometry	SR+HR	annually	1	Night	distortion, scale	1 pixel
Imaging Sky Flats	SR	weekly (1)	4	Twilight	normalized flat	2%
	HR	as needed	4	Twilight	normalized flat	2%
UBVRI photom. std	SR	nightly (1,2)	1	Night	zero points	5%
UBVRI photom. std	HR	as needed	1	Night	zero points	5%
Flux std Gunn & other filters	SR+HR	as needed	1	Night	response	10%
AM > 1.6 UBVRI std	SR+HR	weekly (1,2)	1	Night	extinction coeff.	5%
Screen Flats LSS, MOS, MXU, ECH	SR+HR	as needed	5	Day	normalized flat	5%
Screen Arcs LSS, MOS, MXU, ECH	SR+HR	as needed	1	Day	dispersion coeff.	0.3 pixel (3)
Flux std spectroscopic	SR+HR	as needed (5)	1	Night	response	10%
Imaging Sky Flats without polarizers	SR	as needed	4	Twilight	normalized flat	2%
IPOL polarized std	SR	as needed	1	Night	zero angle (lin)	1 degree
IPOL unpolarized std	SR	annually	1	Night	instr. pol (lin)	
IPOL unpolarized std	SR	annually	1	Night	instr. pol (cir)	
PMOS arcs	SR	as needed	1	Day	dispersion coeff.	0.3 pixel (3)
PMOS flats (45 degree)	SR	as needed	5	Day	normalized flat	5%
PMOS polarized std	SR	as needed	1	Night	zero angle (lin)	1 degree
PMOS unpolarized std	SR	annually	1	Night	instr. pol (lin)	
PMOS unpolarized std	SR	annually	1	Night	instr. pol (cir)	

Table 4.1: FORS Calibration Plan Tasks
(1) only during FORS observing runs; (2) for (U)BVRI filters only and under photometric conditions only; (3) internal accuracy - not considering instrumental flexures - see section 2.4.3; (4) Frequency as needed denotes that the calibration task is done if the subsequent mode was used; (5) Please note that the flux std to calibrate LSS mode is taken with a MOS slit of 5” (at the center of the field) to include all the flux. If you want the std to be observed with the same LSS slit you have to provide a special calibration OB.

10. any IPOL day or night time calibrations with COLL_HR

The observatory staff will prepare a day-time calibration OB in the morning with biases, screen flats and arc-lamp spectra for all spectroscopic and spectro-polarimetric setups. This is done with the semi-automatic calobBuilt software. Calibrations according to item 5 and 6 are hard to configure in an automatic tool and therefore not included in the calibration plan. Calibrations according to item 8 and 9 are thought to be not very usefull for the data reduction and therefore not included. In all other cases the respective calibrations are not supported by the calibration plan to keep the time for the calibration plan within some reasonable limits. The daily maintenance activities of telescope and instruments must not be compromised by extensive calibration requests by visiting or staff astronomers. We will have to keep it as short as possible or the calibrations must be interupted (postponed or even partly canceled,. . .) in case of scheduled or urgent maintenance and setup activities.

4.2 Image Field Distortion and Scales

The image distortion was measured on an astrometric standard star field in 47Tuc (Tucholke 1992, A&AS 93, 293) for FORS1 and FORS2 and in the field of cluster Pal 3 for FORS2 (SDSS coordinates). This method is limited by the accuracy of the astrometric positions of the stars. The measurements were done with FORS1 in the Bessel V band. A third order polynomial was fitted to the measured data. The formulas to determine the deviation (in pixel) of the position measured on the detector from the real (astrometric) position (r in pixel) are given in the table. The measured distortion is in agreement with the design data (SR 0.30%, HR 1.55% at the corner of the field). The residuals of the fit were 0.05 pixels in SR and 0.06 pixels in HR mode.

FORS1 SR: $\Delta r = 2.091 * 10^{-9} * r^3 - 1.228 * 10^{-6} * r^2 + 0.360 * 10^{-3} * r$
FORS1 HR: $\Delta r = 9.515 * 10^{-9} * r^3 - 3.605 * 10^{-6} * r^2 + 1.001 * 10^{-3} * r$

The radial offset derived from the equations above has to be subtracted from the measured position on the CCD. The radius r is calculated from the reference pixel (fits keywords CRPIX1 and CRPIX2) of the world coordinate system. From the optics design it was estimated that the chromatic and thermal effects are of the order of 10% of the distortion.

The radial field distortion of FORS2 was measured with a pinhole MXU mask. The offsets are expressed in units of 24 micron pixels even though measured with 15 micron pixels of the new MIT detectors ($\Delta r'$ and r' in pixels measured on the MIT CCDs):

FORS2 SR: $\Delta r = 2.113 * 10^{-9} * r^3 - 2.158 * 10^{-6} * r^2 + 0.537 * 10^{-3} * r$
FORS2 HR: $\Delta r = 7.133 * 10^{-9} * r^3 + 3.782 * 10^{-6} * r^2 + 0.160 * 10^{-3} * r$

with: $r = r' * (15/24 * \text{binning})$
$\Delta r' = \Delta r / (15/24 * \text{binning})$

The images scale was determined using astrometric standard stars in the star clusters 47Tuc and Pal 3 in several nights during commissioning of the instruments. The plate scales have also been measured in June 2004 when FORS2 was moved to Antu and FORS1 to Kueyen. In this case three fields of standard UCAC2 stars in the vicinity of the cluster Ω Centauri have been used. The measured values are given in the table. For FORS2 the scale is given for unbinned 15 micron pixels in SR mode.

FORS/UT	Coll.	Target	Filter	Scale (arcsec/pix)
FORS1/Antu	SR	47Tuc	I	0.20013±0.00005
FORS1/Antu	HR	47Tuc	I	0.09975±0.00004
FORS2/Yepun	SR	47Tuc	I	0.12604±0.00003
FORS2/Yepun	SR	Pal 3	I	0.12607±0.00003
FORS2/Yepun	HR	Pal 3	I	0.06323±0.00003
FORS/UT (June 2004)	Coll.	Target	Filter	Scale (arcsec/pix)
FORS1/Kueyen	SR	Ω Cen	I	0.20036±0.00008
FORS1/Kueyen	SR	Ω Cen	I	0.20047±0.00007
FORS2/Antu	SR	Ω Cen	I	0.12591±0.00002
FORS2/Antu	SR	Ω Cen	I	0.12591±0.00002
FORS2/Antu	SR	Ω Cen	I	0.12590±0.00003

4.3 Data Reduction of Pre-Imaging Data for the Mask Preparation

Pre-imaging data delivery: As soon as a pre-image is successfully taken, the data will be immediately transfered to the ESO data archive in Garching, where it will be automatically reduced (bias subtraction and flat fielding). Reduced and raw data will then be available on a dedicated ftp account. Detailed instructions on where to retrieve the data from, as well as further information is send to the user by e-mail, typically the day after the pre-image was taken. Please note that the data must be fetched from its ftp location within a certain range of time, usually within a week. The data delivery process starts as soon as the first pre-image is taken, i.e. not only after the whole pre-imaging run is completed.

Shift and add only: The mask preparation for FORS MOS, PMOS and MXU modes will require that the original scale and field distortion is the same in reduced data as it was for the raw data. This is required since the fims tool will correct for the scale distortion in case of FORS pre-images at the time when the masks are saved. Advanced techniques to combine jitter images such as drizzle will require some distortion corrections before the techniques will be applied. It is strongly recommended only to use clean shift and add techniques (eg. IRAF imcombine) to reduce images which are thought to be used for fims mask preparation.

MIT mosaic - don't cut the edges: In case of pre-imaging data taken with the MIT mosaic detector it will be required to keep the original file format of the pre-images. Vignetted parts of the images and pre- and overscan regions must not be cut before using the files with fims. The plug-in function fsmosaic delivered with the fims software can be used to merge the two files safely:

```
fsmosaic RAW_INPUT_FILE OUTPUT_FILE
```

The merged output files could be now combined with standard software such as imcombine (eg. for IRAF imcombine: a median of the jittered files with the offset parameter set to wcs should give satisfactory results for the mask preparations). In general: 1st fsmosaic and then imcombine!

Pipeline support: The quality control group is planning to deliver reduced science frames to applicants which have requested pre-imaging runs with the MIT mosaic. The reduced and merged files can be combined with the standard tools.

The description of the functionality of the fsmosaic plug-in is given in the fims manual (see section 1).

4.4 Flat-Fielding

4.4.1 Imaging Mode

Best results for flat fielding are obtained if the illumination is as similar as possible to that of the science frames. This can be achieved from 4 science frames with adequate S/N of the sky background taken with offsets of >5″; fields should not be too crowded as well. This observing mode is supported by the corresponding templates. In order to achieve a suitable S/N of the resulting super-flatfield, a larger number of science frames may be needed if the sky level is low. If this is not guaranteed, twilight sky flats should be taken in addition. Night flats need to be carefully checked for remaining stars. Master night flats are processed by the reduction pipeline.

Templates are also available which for any desired filter generate sky flats during dusk or dawn, automatically determining the required exposure time from a brief windowed exposure and taking into account the decreasing or increasing sky brightness in the evening or morning. Flat fielding from these exposures will however not remove large scale gradients (of the order of 1000 pixels). In service mode twilight flats are provided as standard calibration frames.

Screen flatfields can be taken (see section 2.9) with the internal lamps and the screen in the telescope. A guide to approximate exposure times is given in Table 4.3. Screen flats should be used only for removing the high-frequency component of the flat field. However, this can be equally well achieved using sky flats, since the exposure levels in both are comparable. Furthermore, screen flats contain artificial reflections off the LADC (2-3 dots close to the image center) which need to be removed before applying. Screen flats are not provided as standard calibration frames in service mode, but need to be requested.

Table 4.2 lists results from the analysis of the flatfields (including master flats produced by the pipeline) taken during the past periods. The “sigma” values scale as sqrt(exposure level). All other values scale with the exposure level. “sigma” in masters goes down by a factor sqrt(N) where N is the number of raw files contributing. “diff_AB” is the fractional gain difference between ports A and B which is removed by the flattening. “gradient” is the ’large’-scale gradient measured in a window of size 200x200 pixels.

Typical exposure level (ADU)	sigma noise, photon (raw)	sigma noise, fixed pattern	diff_AB	gradient (200^2)
20000	0.6%	0.5%	18-25%	0.7%

Table 4.2: Large-scale structure and small-scale noise in sky flats (high gain CCD readout)

Table 4.3 gives typical exposure times for screen flats for the SR collimator and Bessell filters. The numbers are indicative only since they are subject to changes due for instance lamp replacements. The observatory staff has updated values at hand and takes also care of proper adjustments of the calibration exposure times for delivered service mode OBs (unless otherwise stated in the readme file of the program).

4.4.2 Spectroscopic Modes

For the spectroscopic modes one will use internal screen flats in most cases. These flats are taken during daytime with the telescope pointing to zenith and the instrument in calibration position. Spectroscopic flats on the sky in twilight are not supported by the FORS standard templates.

A guide to exposure times is given in Table 4.4. In MOS mode some bleeding from zero order may occur for low dispersion grisms and unfavorable (i.e. wide spread in dispersion direction) object geometry. The numbers are indicative

Lamp	U_SPECIAL	B	V	R	I
Blue+1	+	+	+	+	+
Blue+2	+	+	+	+	+
Red+1	–	–	–	–	–
Red+2	–	–	–	–	–
exp. time	200	4	4	6	10

Table 4.3: Approximate exposure times (seconds) for FORS2 imaging screen flat calibrations for the Bessell and special broadband filters, SR collimator, high gain readout

only since they are subject to changes due for instance lamp replacements. The observatory staff has updated values at hand and takes also care of proper adjustments of the calibration exposure times for delivered service mode OBs (unless otherwise stated in the readme file).

Grism	OSF	Exposure time	
		FORS1	FORS2
1400V	—		27.3
1200R	GG435		11.5
1028z	OG590		9.1
600B	—	40.0	8.3
600R	GG435	38.4	
600I	OG590	34.0	7.0
	F465_250		40.0
600RI	GG435		3.8
600z	OG590		5.2
	F465_250		45.4
300V	—/GG375/GG435	13.0	9.0
300I	—/OG590	9.8	4.0
200I	—		1.2
150I	—/OG590/GG375/GG435	5.1	1.1
110B	Echelle	TBD	TBD

Table 4.4: Approximate exposure times (seconds) for FORS2 spectroscopic screen flat calibrations with FORS2. Flat-field lamps of one calibration unit switched on. Approximate exposure level is 30000 ADU. Slit width = 1″, SR collimator, high gain readout, 2x2 binning.

4.5 Wavelength Calibration

For the wavelength calibration one may use the He and Ar lamps (at the lowest spectral resolution — grism 150I) and in addition the Ne lamp (at higher resolution). Note that the exposure time of the Ne lamp should be reduced by a factor of 5 at least (switch-on times can be defined individually for each lamp in the corresponding calibration template). For grism 600B the HgCd lamp must be used. Approximate exposure times for well exposed spectra are given in Table 4.5 for the different grisms and lamps, for a slit width of 1″. Calibration spectra taken with the different grisms are plotted in figures D.4–D.21.

The numbers are indicative only since they are subject to changes due to e.g. lamp replacements. The observatory staff has updated values at hand and takes also care of proper adjustments of the calibration exposure times for delivered service mode OBs (unless otherwise stated in the README file).

Wavelength calibration exposures are done during the day only with the telescope in zenith and the instrument in calibration position.

Grism	OSF	He	HgCd	2*Ar	2*Ne
1400V	—	100	25	0	100
1200R	GG435	75	0	37	7
1028z	OG590	100	0	5.5	100
600B	—	100	25	0	0
600I	OG590	7	0	7	7
	F465_250	250	125	0	0
600RI	GG435	90	40	4.5	4.5
600z	OG590	75	0	4.5	75
	F465_250	250	140	0	0
300V	—/GG375/GG435	70	17.5	9.8	0
300I	OG590	100	0	5	0
200I	—	70	0	4.9	0
150I	—/OG590/GG375/GG435	60	18	6	0
110B	Echelle	300	111	0	0

Table 4.5: Approximate exposure times and switch-on times of calibration lamps (seconds) for FORS2 wavelength calibrations with FORS2. Any slit width, SR collimator, high gain readout, 2x2 binning. The update with the integration times for FORS1 is still pending.

4.6 Calibrating Polarimetric Measurements

4.6.1 Circular polarimetry

The amount of circular polarization V can be determined, observing with the quarter wave retarder plate at two retarder plate angles of $\theta = \pm 45^\circ$, by the equation:

$$V = \frac{1}{2}\left[\left(\frac{f^o - f^e}{f^o + f^e}\right)_{\theta=45} - \left(\frac{f^o - f^e}{f^o + f^e}\right)_{\theta=-45}\right] \tag{4.1}$$

(f^o, f^e being the ordinary and extraordinary beam of the object measured for a given retarder plate angle θ)

One could determine the circular polarization observing at one retarder plate position, but two observations are required to eliminate the strongest observing biases in the first order approximation:

- the improper flat field correction ϵ_{FF}
- the color dependent offset ϵ_θ to the nominal retarder plate zero angle
- the incomplete and color dependent retardation of $90 + \epsilon_\Phi(\lambda)$ degree of the quarter wave plate

Observations at only one retarder plate angle would cause hardly correctable Stokes parameter cross talks in the case of objects with non-negligible linear polarization. The color dependence of the retarder angle ϵ_θ would cause an additional polarization of $\Delta V = -2\epsilon_\theta U$ and the incomplete retardation ϵ_Φ ($\Phi \neq 90$ degree, quarter wave) would cause the additional polarization of $\Delta V = -\epsilon_\Phi Q$ (ϵ_Φ & ϵ_θ in radians, UVQ being the Stokes parameters). One would get

$$\left(\frac{f^o - f^e}{f^o + f^e}\right)_{\theta=45} = V + \epsilon_{FF} + (-2\epsilon_\theta U - \epsilon_\Phi Q) \tag{4.2}$$

$$\left(\frac{f^o - f^e}{f^o + f^e}\right)_{\theta=-45} = -V + \epsilon_{FF} + (-2\epsilon_\theta U - \epsilon_\Phi Q) \tag{4.3}$$

The difference between the two observations yields V while the small deviations have the same sign in the two equations and are therefore eliminated for small angles ϵ_Φ & ϵ_θ.

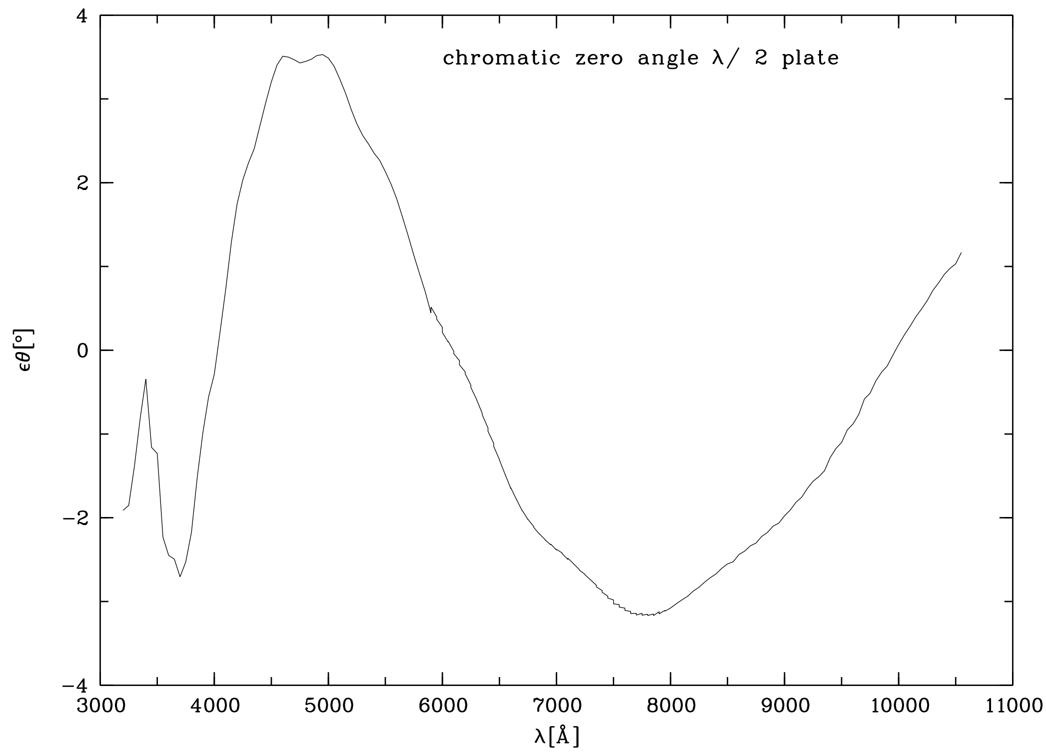

Figure 4.1: Zero angle chromatism of the half wave plate

4.6.2 Linear Polarimetry

After the pre-reduction of the spectroscopic data and integration of the ordinary and extraordinary target spectra or flux $f^o(\theta_i)$ and $f^e(\theta_i)$, the normalized flux differences $F(\theta_i)$ must be calculated:

$$F(\theta_i) = \frac{f^o(\theta_i) - f^e(\theta_i)}{f^o(\theta_i) + f^e(\theta_i)}, \tag{4.4}$$

where $\theta_i = i * 22.5°$ is the angle of the retarder plate ($0 < i < 15$).

If the polarimetry is obtained from the normalized flux differences, no absolute flux calibration of the data is required.

zero angles – imaging mode	
Filter	ϵ_θ
Bessel U	-2.07deg
Bessel B	+1.54deg
Bessel V	+1.80deg
Bessel R	-1.19deg
Bessel I	-2.89deg
Gunn u	-2.03deg
Gunn v	-0.47deg
Gunn g	+3.10deg
Gunn r	-1.31deg
Gunn z	-1.64deg

Table 4.6: Calibration of the FORS1 half wave retarder plate in imaging mode from the spectroscopic measurements with the Glan-Thompson prism. These values will depend slightly on the color of the observed targets.

In this case, the Stokes parameters Q and U can be derived via Fourier transformation:

$$Q = \sum_{i=0}^{N-1} \frac{2}{N} F(\theta_i) \cos(4\theta_i) \quad (4.5)$$

$$U = \sum_{i=0}^{N-1} \frac{2}{N} F(\theta_i) \sin(4\theta_i) \quad (4.6)$$

In principle, two observations at different retarder angles ($N = 2$) are sufficient to calculate Q and U. At least four measurements at angle 0.0 to 67.5 are needed to suppress the impact of the improper flat fielding of the data. Best results will be obtained, if observations at all the rotation angles of the retarder plate ($N = 16$) will be carried out.

Although a super-achromatic half wave plate is used with FORS, the zero angle of the plate is not negligible. Therefore all raw measurements of polarization position angles are rotated by an angle of a few degrees. For the half wave plate the chromatic dependence of the zero angle was determined with an aligned Glan-Thomson prism. The tabulated values of the zero angle as displayed on figure 4.1 can be obtained on request.

For imaging polarimetry the offset angles can be determined by convolving the filter response curves with the color dependence of the half wave plate. The results are given in Table 4.6.

Measuring a polarization angle of e.g. $\theta = 134.20$ deg in the Bessel B filter one would correct this raw measurement to a final result of $\theta = 132.66$ deg. The offset angles should be confirmed periodically by the observation of polarized standard stars.

4.7 Pipeline Reduction

A data reduction pipeline is operational for FORS1 and FORS2.

4.7.1 Supported modes

The FORS pipeline presently supports two instrumental modes: imaging (IMG) and longslit spectroscopy (LSS). It provides :

- creation of master calibration products
- reduction of science data
- photometric zero points and spectral response

For IMG data, the raw data are bias subtracted and flat fielded. The single frames taken within a sequence are not combined. LSS data, in addition to de-biasing and flat fielding (high spatial frequencies only), are rebinned to wavelength space. No correction for instrumental response is done. No night sky subtraction and source extraction is applied and the single frames taken within a sequence are not combined.

4.7.2 Quality Control Pipeline - Service Mode Only

All data taken in service mode are reduced by the quality control group in Garching:

Master Calibration Data: As part of the service mode concept, the master calibration data set is provided to the service mode observer. All raw calibration data from the pipeline-supported modes of FORS (regardless of whether they are obtained in visitor or in service mode) are processed to obtain master calibration data. These are optimized for e.g. low noise level, and they are quality-checked. Hence they give the optimum calibration data to the best present knowledge.

Master calibration data are of the following types:

- master_BIAS (bias level, read-out noise),
- master_SCREEN_FLAT_IMG (high spatial frequency flat),

- master_SKY_FLAT_IMG (high and low spatial frequency flat, taken in twilight),
- master_NIGHT_FLAT_IMG (as previous, obtained from night science exposures),
- photometric zero points (from standard star observations),
- bad-pixel tables,
- master_SCREEN_FLAT_LSS (high spatial frequency flat, slit function),
- WAVE_DISPERSION_LSS (wavelength calibration).

Usually master_SKY_FLAT_IMG are used for flattening IMG data. This removes all multiplicative artifacts in the image (different gain values in the four CCD ports, pixel-to-pixel gain variations, instrument and CCD efficiency). Since the illumination during dusk/dawn is, however, different from night conditions, a large-scale gradient of a few percent may remain which can be easily removed by e.g. fitting a polynomial.

A better large-scale illumination correction can be obtained from night flats which are pipeline-processed from jittered science images. Since these usually have a lower signal-to-noise ratio than lamp flats, it is preferable to use them for large-scale correction only.

Photometric zero points are routinely calculated for the standard Bessell or special broadband filters of the instrument. They are provided to the users as part of the service mode package. They will be published on the web instrument page.

Science Data: science data are pipeline-processed if they are obtained in service mode. Any standard mode IMG observation (either of the 4 CCD modes if 1x1 binning, no window; one of the 5 standard filters; either collimator) can expect a reduced file. LSS observations are reduced if taken in single port readout mode.

4.7.3 Paranal Science Operation Pipeline — IMG, LSS mode only

In parallel to Garching, the FORS pipeline is in operation on Paranal. This allows the staff and visiting astronomer to better estimate the quality of the data. The on-site pipeline is operated with calibration data provided by the quality control group and therefore are not the most recent ones. Note also that the calibration database can be incomplete (in particular in longslit mode) due to the high number of longslits, grisms and filters combinations, and therefore only a part of the data will be processed.

The Paranal pipeline works on a dedicated machine. Reduced science data are computed shortly after they have been exposed and are transmitted for inspection to the off-line user workstation.

The on-site pipeline will deliver the following products:

- master bias frames
- master twilight flats (IMG mode)
- flat fielded science images (IMG mode)
- photometric zero points (IMG mode)
- master screen flats (LSS mode)
- flat fielded science images (only for a few slit/grism combinations) (LSS mode)

Appendix A

Abbreviations and Acronyms

The following abbreviations and acronyms are used in this manual:

ACQ	Acquisition
ADU	Analogue-to-Digital Unite
BOB	Broker of Observation Blocks
CCD	Charge Coupled Device
DDTC	Director's Discretionary Time Committee
DSS	Digital Sky Survey
ECH	Echelle Spectroscopy
ESO	European Southern Observatory
ETC	Exposure Time Calculator
FIERA	Fast Imager Electronic Readout Assembly
FIMS	FORS Instrumental Mask Simulator
FITS	Flexible Image Transport System
FORS	Focal Reducer/Low Dispersion Spectrograph
FWHM	Full Width Half Maximum
HIT	HIgh-Time resolution
HR	High Resolution
IDL	Interactive Data Language
IMG	Imaging
IPOL	Imaging Polarimetry
IRAF	Image Reduction and Analysis Facility
ISF	Instrument Summary File
LADC	Longitudinal Atmospheric Dispersion Compensator
LSS	Long Slit Spectroscopy
MIDAS	Munich Image Data Analysis System
MOS	Multi Object Spectroscopy
MXU	Mask eXchange Unit
OB	Observation Block
OSF	Order Separation Filter
OT	Observing Tool
PMOS	Polarimetric Multi Object Spectroscopy
PSF	Point Spread Function
P2PP	Phase 2 Proposal Preparation
RMS	Root Mean Square
RON	Read Out Noise
RQE	Responsive Quantum Efficiency
SR	Standard Resolution
S/N	Signal-to-Noise
TBC	To Be Confirmed
TBD	To Be Defined
TCS	Telescope Control System

UV	Ultraviolet
VIMOS	Visible Multi-Object Spectrograph
VLT	Very Large Telescope
WCS	World Coordinate System

Å	Ångstrom
e^-	Electron
cm	Centimeter
h	Hour
kpx	KiloPixel
min	Minute
mm	Millimeter
nm	Nanometer
px	Pixel
s	Second
μm	Micrometer

Appendix B

FORS Filter Characteristics

B.1 Broadband Filters

Table B.1 lists all presently (see issue date of this document) available FORS1 and FORS2 broadband filters. The transmission curves are given thereafter. Note: the transmission curve of filter U_SPECIAL+73 is not yet available. Tables of the measured transmission values will be available via the ESO web pages:

`http://www.eso.org/instruments/fors/filters.html`

Instrument	Filter	λ_0 (nm)	FWHM (nm)
FORS1	U_BESS+33 (1)	366	36.0
FORS2	U_SPECIAL+73	362	29.0
FORS1/2	B_BESS+34/+74 (2)	429	88.0
FORS1/2	V_BESS+35/+75	554	111.5
FORS1	R_BESS+36	657	150.0
FORS2	R_SPECIAL+76	655	165.0
FORS1/2	I_BESS+37/+77	768	138.0
FORS1	u_GUNN+38	359	33.5
FORS1	v_GUNN+39	398	46.0
FORS1	g_GUNN+40 (3)	506	79.5
FORS1	r_GUNN+41	653	81.5
FORS1	z_GUNN+42/+78	910	130.5
FORS1/2	GG375+30/+80 (4)	edge filter: n/a	n/a
FORS1/2	GG435+31/+81 (4)	edge filter: n/a	n/a
FORS1/2	OG590+72/+32 (4)	edge filter: n/a	n/a
FORS2	FILT_465_250+82 (4)	465	250

Table B.1: Characteristics of the FORS1/2 broadband filters. λ_0 is the central wavelength in nm.
(1) red leak $< 7 \times 10^{-5}$
(2) red leak $< 4 \times 10^{-4}$
(3) this filter is located in one of the interference filter wheels, as it is physically designed as an interference filter
(4) these are intended as order separation filters for spectroscopy

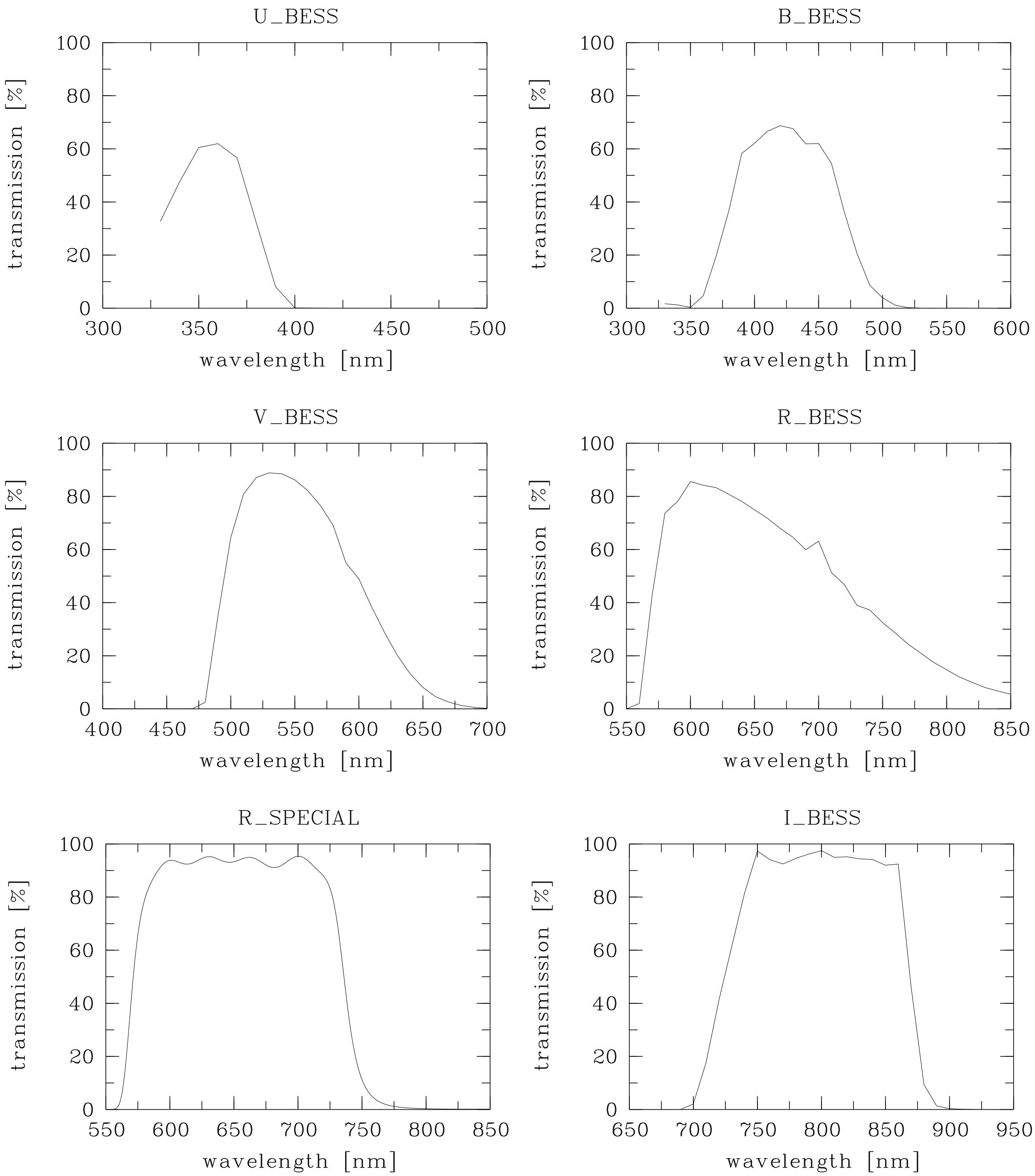

Figure B.1: Bessell filter transmission curves. U_BESS and R_BESS are only available for FORS1. R_SPECIAL is available only for FORS2. U_SPECIAL for FORS2 is still to be measured (see Table B.1 for some preliminary information.

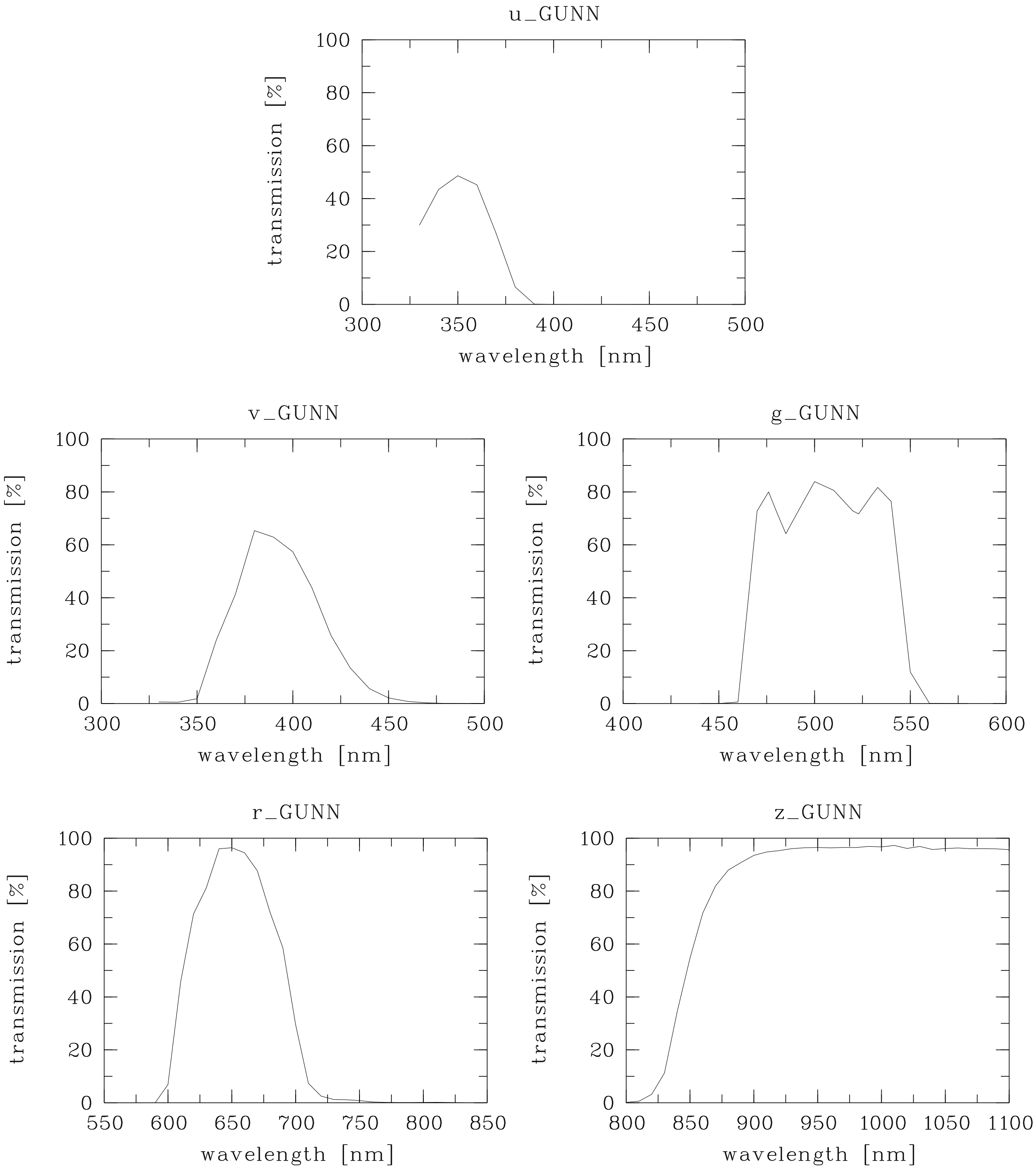

Figure B.2: Gunn filter transmission curves. The Gunn filters uvgr are only available with FORS1. z_GUNN filters are available for both instruments.

B.2 Interference Filters

Table B.2 lists all presently available interference filters used with for FORS1 and FORS2. Their characteristics are given with the FORS SR and HR collimators: central wavelength, peak transmission and FWHM. Due to their location in the converging beam, the filter characteristics depend on the collimator used. The filter bandwidths are wider, the central wavelength is blue-shifted, and the peak transmission is lower than in a parallel beam. With the SR collimator, the effect is larger than with the HR collimator. The filters are centered on important emission lines and on 5 % and 10 % longer wavelengths.

		λ_0		T_0		FWHM (nm)		
Filter	Line	SR	HR	SR	HR	SR	HR	λ_0 shift
OII+44	[OII] 372.7	371.7	372.9	0.45	0.48	7.3	6.9	0%
OII/4000+45		377.6	378.8	0.37	0.40	6.5	6.1	5%
OII/8000+46		381.4	382.6	0.43	0.47	6.5	6.1	10%
HeII+47	HeII 468.6	468.4	469.1	0.79	0.82	6.6	6.4	0%
HeII/3000+48		472.6	473.4	0.76	0.79	5.8	5.6	5%
HeII/6500+49		478.1	478.9	0.78	0.81	6.8	6.6	10%
OIII+50	[OIII] 500.7	500.1	500.9	0.76	0.80	5.7	5.5	0%
OIII/3000+51		504.5	505.3	0.76	0.80	5.9	5.7	5%
OIII/6000+52		510.5	511.3	0.74	0.78	6.1	5.9	10%
HeI+53	HeI 587.6	586.6	587.6	0.79	0.84	6.0	5.7	0%
HeI/2500+54		592.0	593.0	0.77	0.81	6.8	6.5	5%
HeI/5000+55		597.5	598.5	0.85	0.89	7.4	7.2	10%
OI+56	[OI] 630.0	629.5	630.6	0.75	0.79	7.2	6.9	0%
OI/2500+57		635.4	636.4	0.75	0.81	5.9	5.5	5%
OI/4500+58		640.4	641.4	0.77	0.83	6.3	6.0	10%
H_Alpha+83	Hα 656.3	656.3	657.4	0.70	0.76	6.1	5.7	0%
H_Alpha/2500+60		660.4	661.5	0.77	0.83	6.4	6.1	5%
H_Alpha/4500+61		666.5	667.6	0.72	0.77	6.5	6.1	10%
SII+62	[SII] 672.4	672.8	673.9	0.77	0.82	6.6	6.3	0%
SII/2000+63		677.4	678.5	0.77	0.82	6.8	6.5	5%
SII/4500+64		683.2	684.3	0.72	0.78	6.4	6.0	10%
SIII+65	[SIII] 953.2	952.3	953.9	0.68	0.80	5.9	5.2	0%
SIII/1500+66		957.2	958.8	0.72	0.84	6.3	5.6	5%
SIII/1500+67		962.1	963.7	0.70	0.83	5.9	5.2	10%
FILT_485_37		485		0.89		37		
FILT_691_55		691		0.93		55		
FILT_815_13		815		0.90		13		
FILT_834_48		834		0.90		48		
z_SPECIAL		915		0.94		20		
FILT_917_6		917		0.85		6		
FILT_500_5	[OIII] 500.7	500		0.81		5		
FILT_503_5		503		0.83		5		
FILT_530_25		530		0.85		25		

Table B.2: Characteristics of the FORS interference filters. λ_0 is the central wavelength in nm, T_0 the peak transmission.

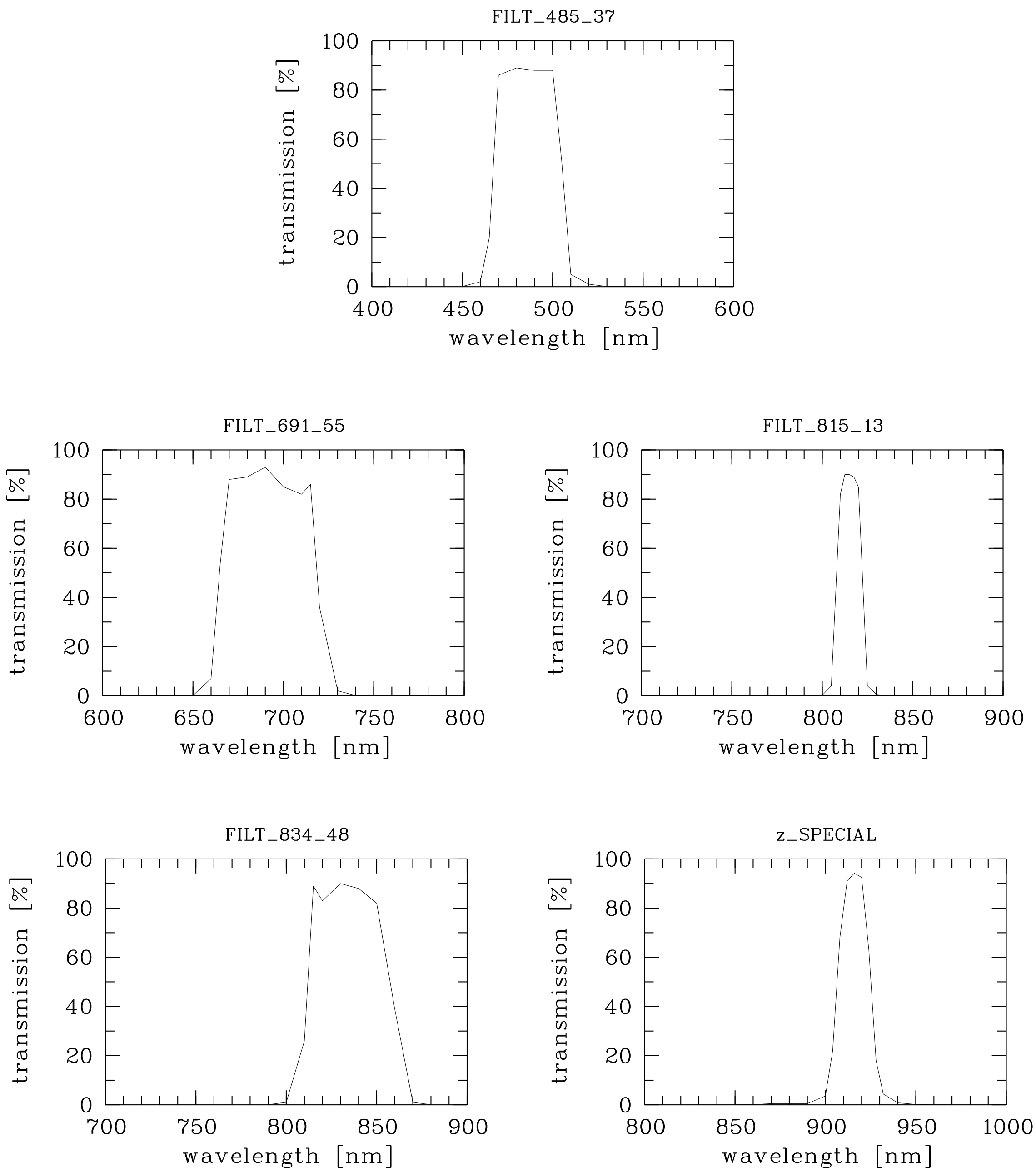

Figure B.3: FORS intermediate band filter transmission curves.

Appendix C

Efficiency Curves for the FORS Grisms

C.1 FORS1 and FORS2 Grisms

This appendix contains the efficiency curves of all standard grisms available for FORS1 and FORS2 and the approximate wavelength range for a slit which is located in the field centre. Tables of the measured efficiency values will be available on WEB pages:

```
http://www.eso.org/instruments/fors/grisms_f1.html
http://www.eso.org/instruments/fors/grisms_f2.html
http://www.eso.org/instruments/fors/grisms_f2_2nd_Order.txt
```

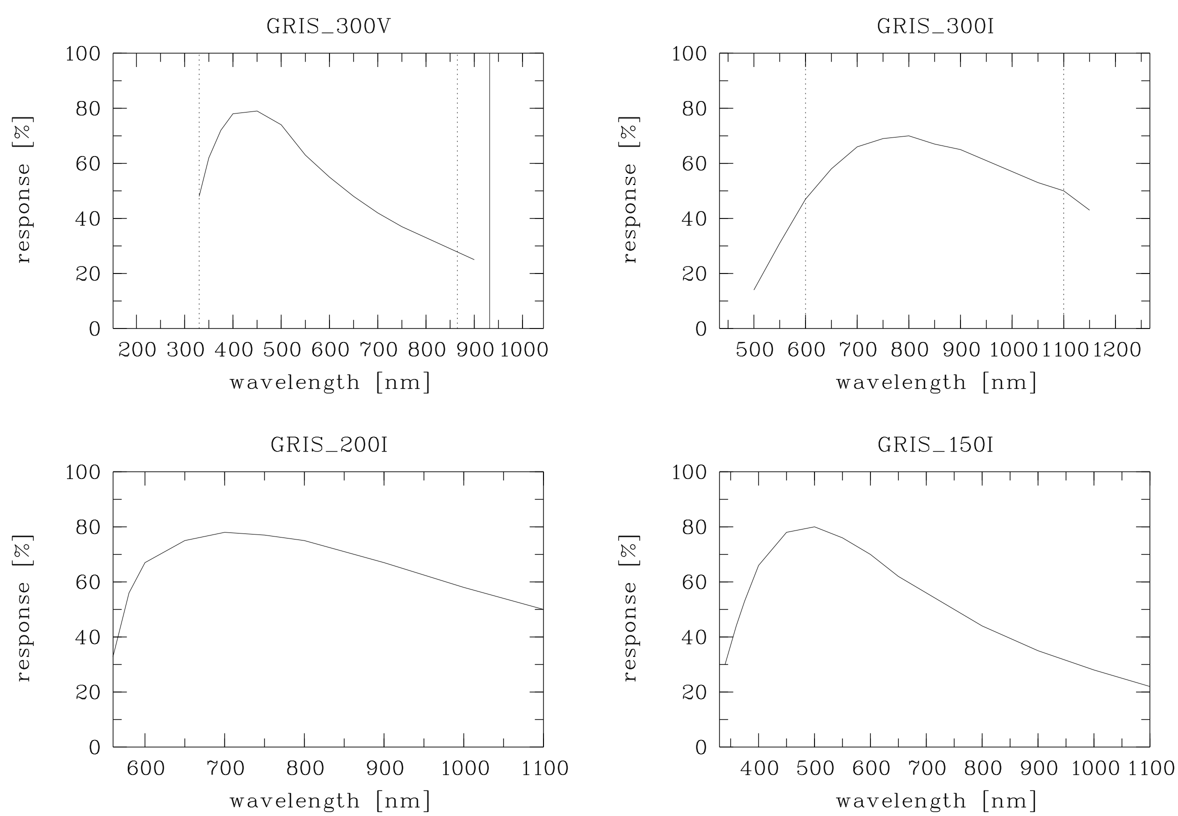

Figure C.1: Efficiency curves of the low resolution grisms. The vertical lines mark the approximate limits of the spectral range with the slit in the center of the field. The cutoff wavelength is in most cases given by the order separation filters, the red CCD limit or the 330nm limit of the FORS optics in the blue.

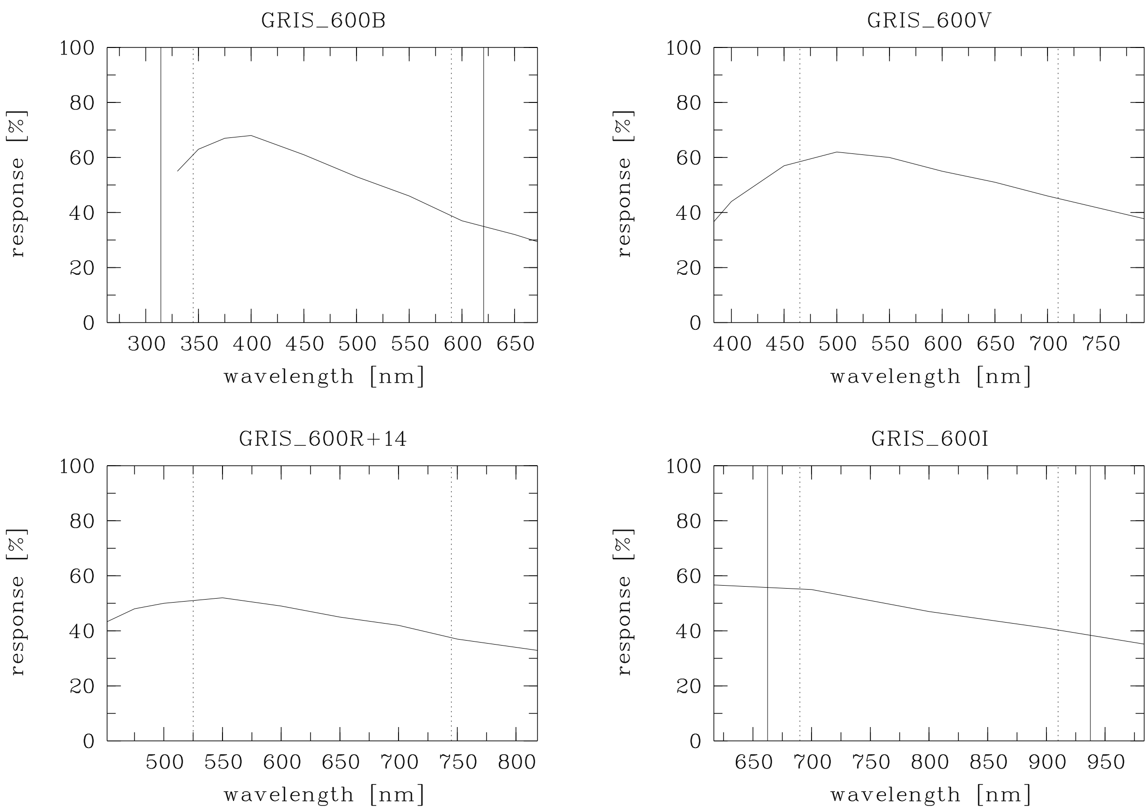

Figure C.2: Efficiency curves of the medium resolution grisms. The vertical lines mark the approximate limits of the spectral range with the slit in the center of the field: dotted lines FORS1, solid lines FORS2

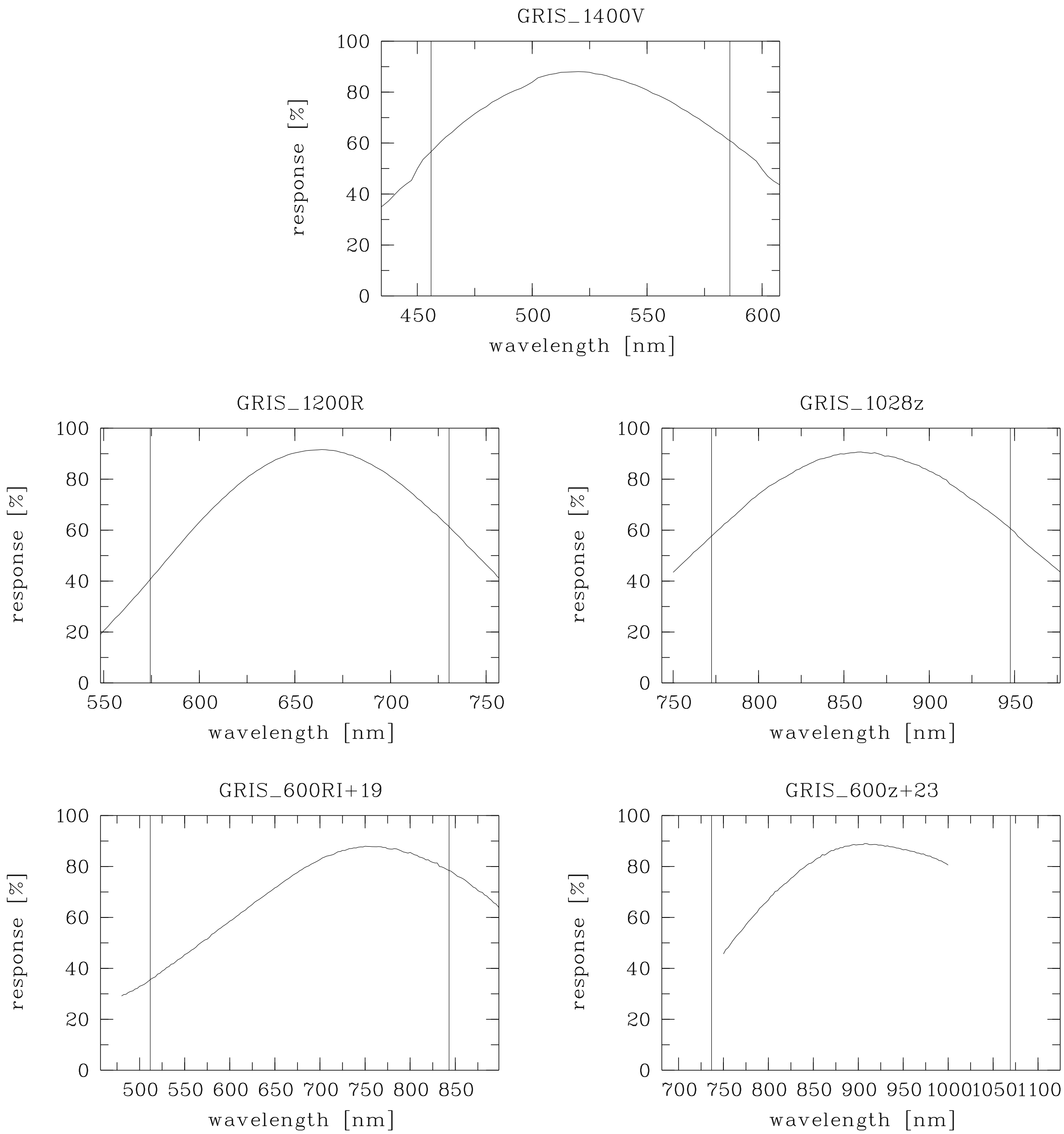

Figure C.3: Efficiency curves of the medium resolution volume phased holographic grisms. The vertical lines mark the approximate limits of the spectral range with the slit in the center of the field: dotted lines FORS1, solid lines FORS2

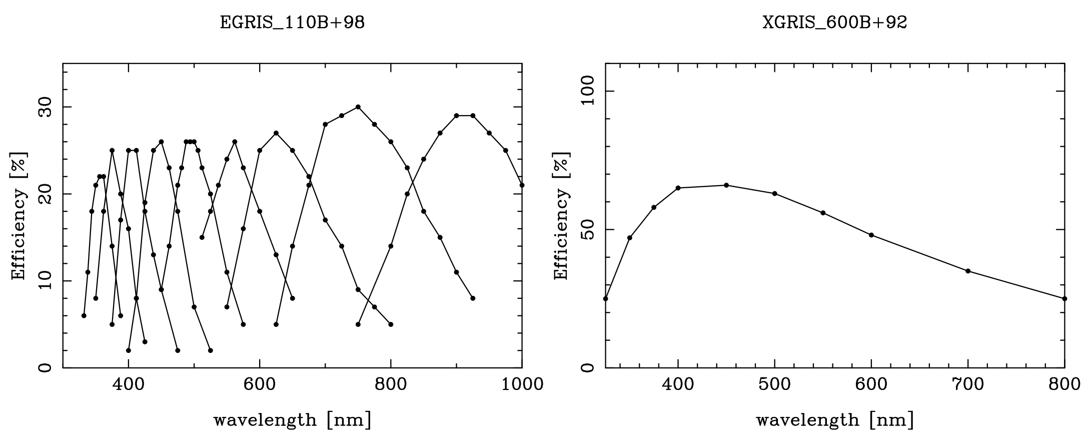

Figure C.4: Efficiency curves of the orders 4–12 of Echelle grism EGRIS_110B+98 and the cross disperser grism XGRIS_600B. The curves of the Echelle orders have to be folded with the efficiency of the cross disperser.

Appendix D

Wavelength Calibration Spectra for the FORS Standard Grisms

This Appendix gives a wavelength table for the calibration lamps used in FORS1 and FORS2 together with the arc line spectra taken with the FORS grisms and the SR collimator. The measurements were done with MOS slits located in the center of the field of view and a slit width of 1.0 arcseconds.

Note: these plots are indicative only, since minor shifts of the wavelength pixels may occur between the two FORS instruments and due to different dewar mounting after instrument and CCD maintenance. The x-scale is in units of binned pixels in case of FORS2.

Wavelength (Å)	Element	Wavelength (Å)	Element
3610.500	Cd	7065.200	He I
3650.144	Hg	7081.880	Hg
3654.840	Hg	7091.990	Hg
3663.274	Hg	7147.041	Ar I
3888.646	He I	7173.939	Ne I
3964.700	He I	7245.167	Ne I
4026.200	He I	7272.930	Ar I
4046.557	Hg	7281.349	He I
4077.831	Hg	7346.200	Cd
4347.500	Hg I	7383.900	Cd
4358.343	Hg	7383.981	Ar I
4471.479	He I	7385.300	Cd
4678.160	Cd	7438.900	Ne I
4713.200	He I	7488.870	Ne I
4799.920	Cd	7503.868	Ar I
4916.070	Hg	7514.652	Ar I
4921.929	He I	7535.800	Ne I
5015.675	He I	7635.106	Ar I
5085.824	Cd	7724.210	Ar I
5341.100	Ne I	7948.176	Ar I
5400.562	Ne I	8006.157	Ar I
5460.742	Hg	8014.786	Ar I
5764.419	Ne I	8103.693	Ar I
5769.598	Hg	8115.311	Ar I
5790.656	Hg	8264.523	Ar I
5852.488	Ne I	8300.326	Ne I
5875.620	He I	8377.367	Ne I
5881.900	Ne I	8408.210	Ar I
5944.830	Ne I	8424.648	Ar I
5975.534	Ne I	8495.360	Ne I
6029.977	Ne I	8521.442	Ar I
6074.338	Ne I	8591.259	Ne I
6096.160	Ne I	8634.648	Ne I
6143.063	Ne I	8654.384	Ne I
6163.594	Ne I	8667.944	Ar I
6217.281	Ne I	8681.900	Ne I
6266.495	Ne I	8704.150	Ne I
6304.790	Ne I	8853.867	Ne I
6334.428	Ne I	8919.500	Ne I
6382.991	Ne I	9122.968	Ar I
6402.246	Ne I	9201.800	Ne I
6438.470	Cd	9224.499	Ar I
6506.528	Ne I	9300.850	Ne I
6532.880	Ne I	9354.218	Ar I
6598.953	Ne I	9425.380	Ne I
6678.149	He I	9657.784	Ar I
6678.300	Ne I	9784.501	Ar I
6717.040	Ne I	10140.000	Hg
6907.160	Hg	10394.600	Cd
6929.468	Ne I	10830.171	He I
6965.431	Ar I		
7032.413	Ne I		

Table D.1: Wavelengths of the arc lamp lines, with the corresponding element

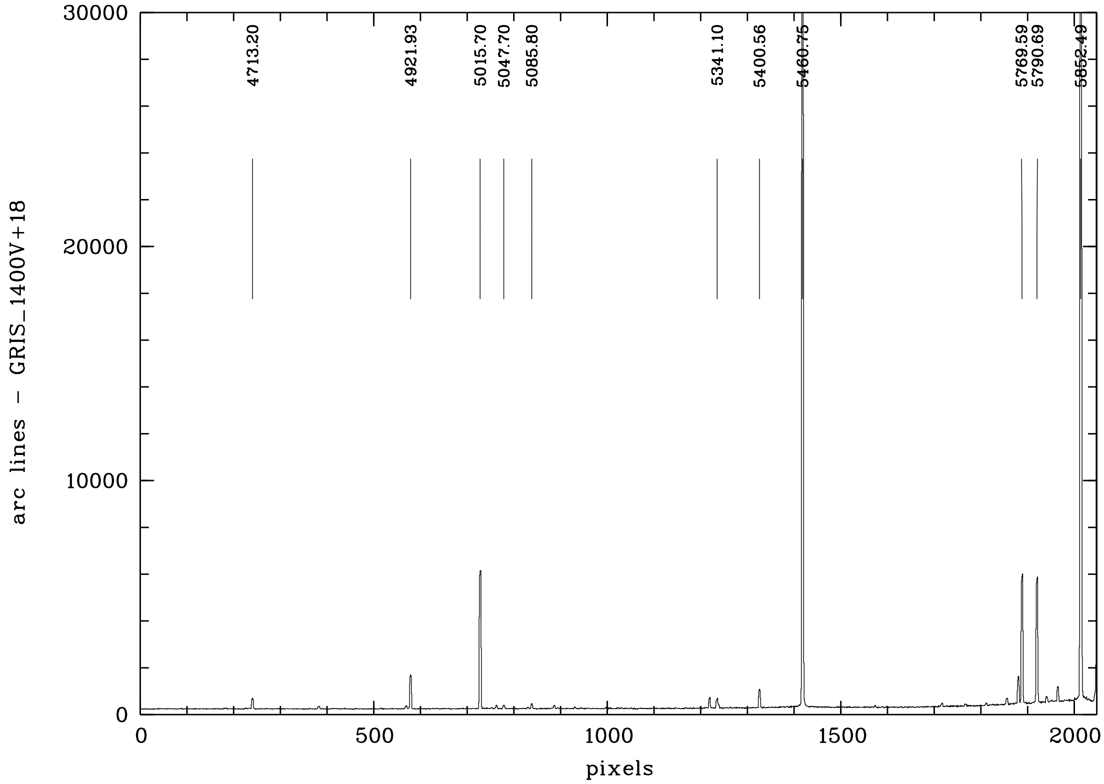

Figure D.1: Calibration spectrum taken with the SR collimator and grism GRIS_1400V+18 (FORS2)

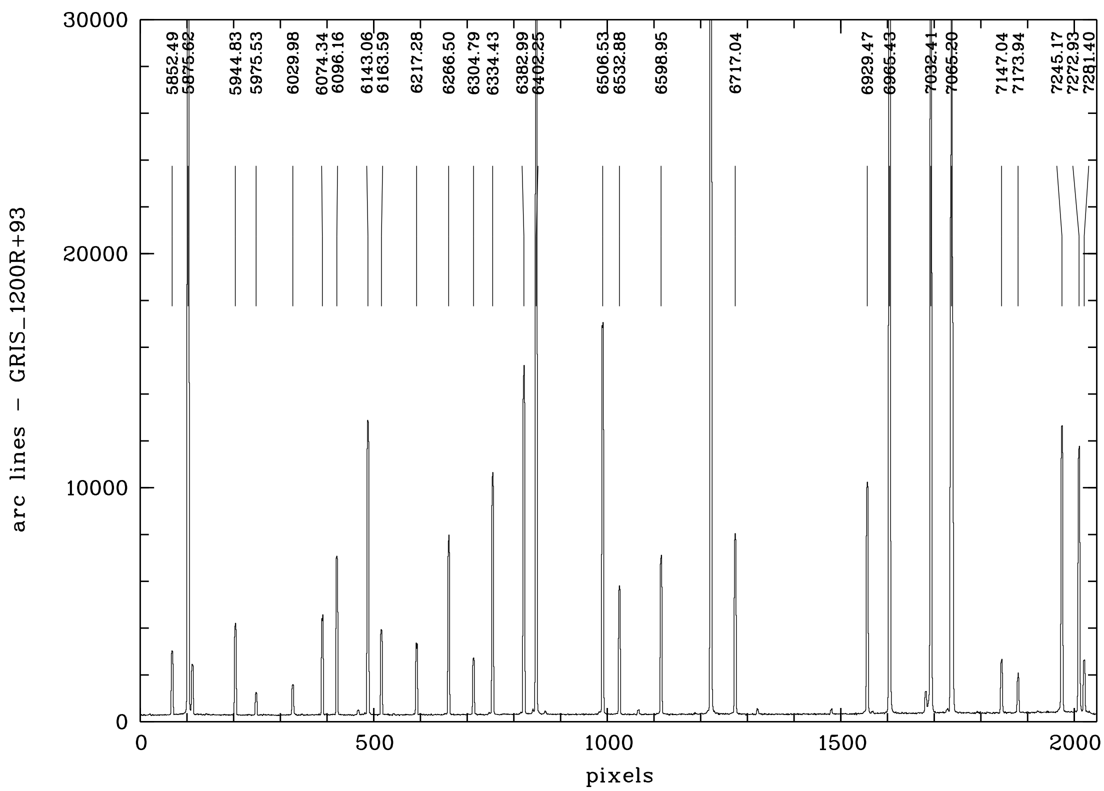

Figure D.2: Calibration spectrum taken with the SR collimator and grism GRIS_1200R+93 (FORS2)

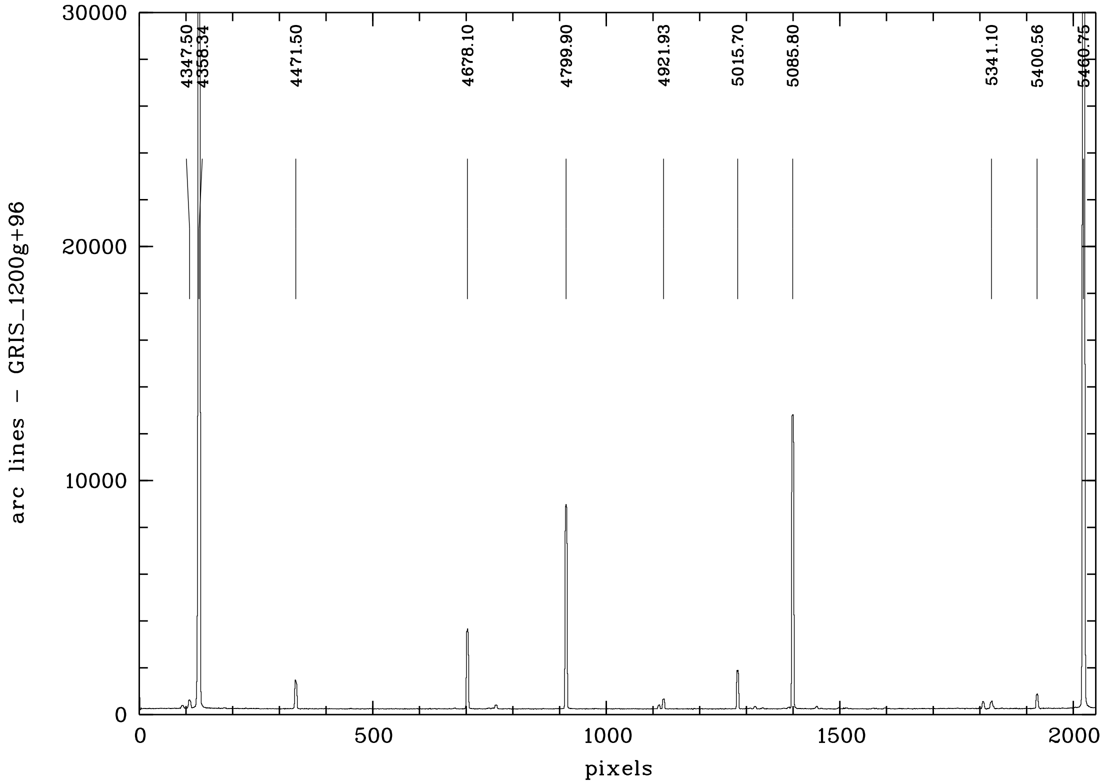

Figure D.3: Calibration spectrum taken with the SR collimator and grism GRIS_1200g+96 (FORS1)

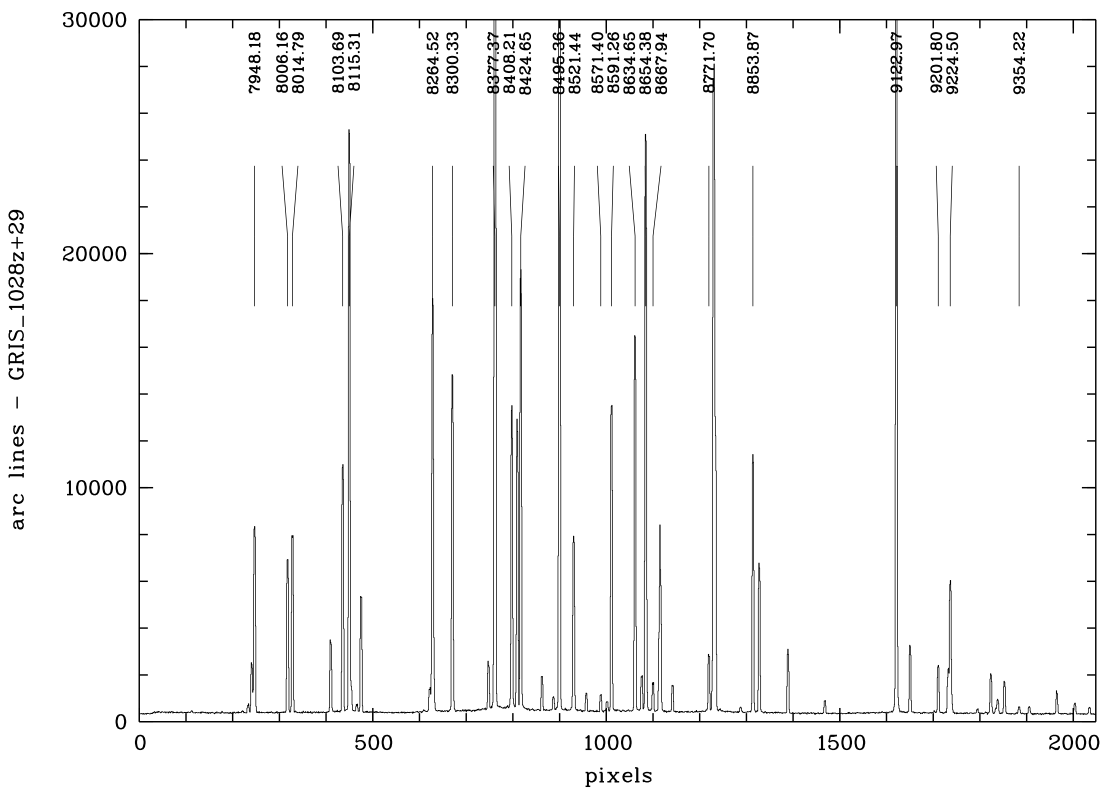

Figure D.4: Calibration spectrum taken with the SR collimator and grism GRIS_1028z+29 (FORS2)

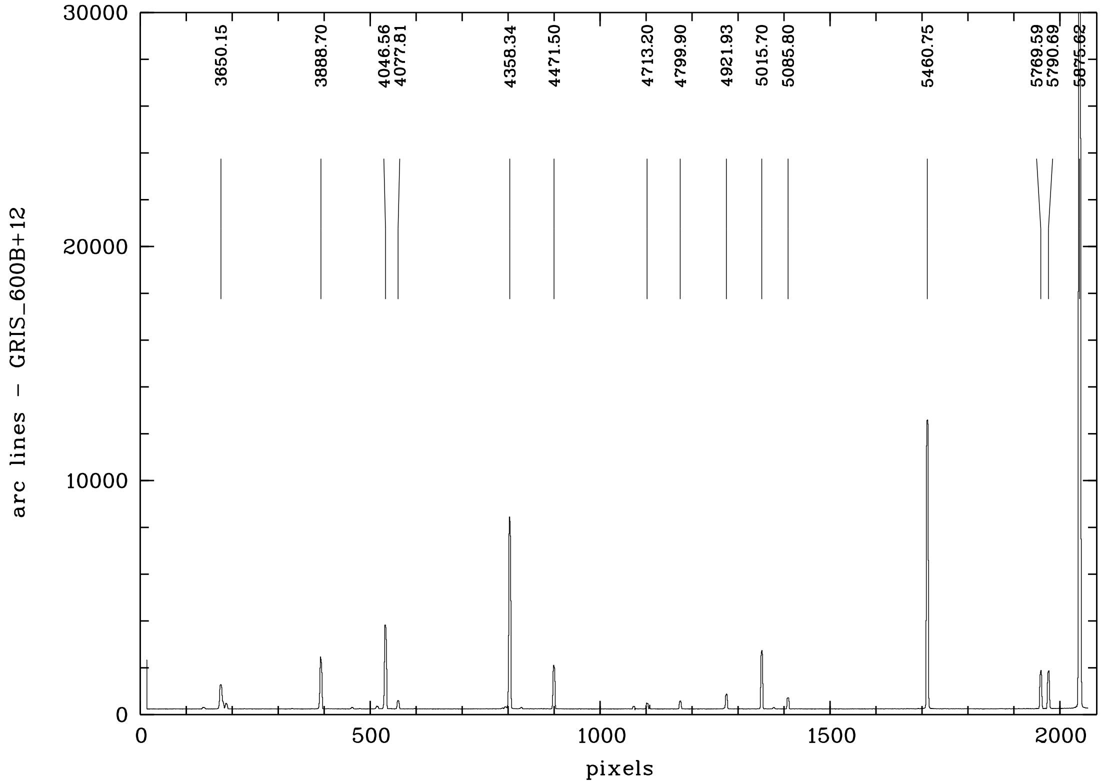

Figure D.5: Calibration spectrum taken with the SR collimator and grism GRIS_600B+12 (FORS1)

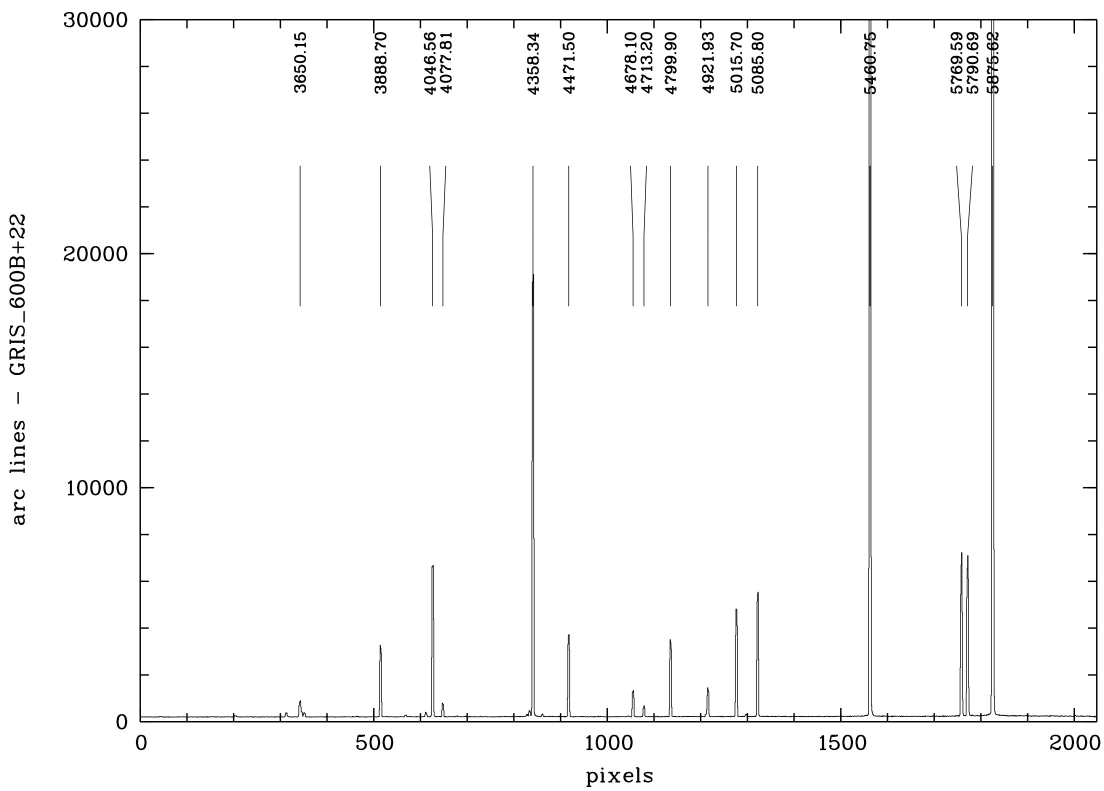

Figure D.6: Calibration spectrum taken with the SR collimator and grism GRIS_600B+22 (FORS2)

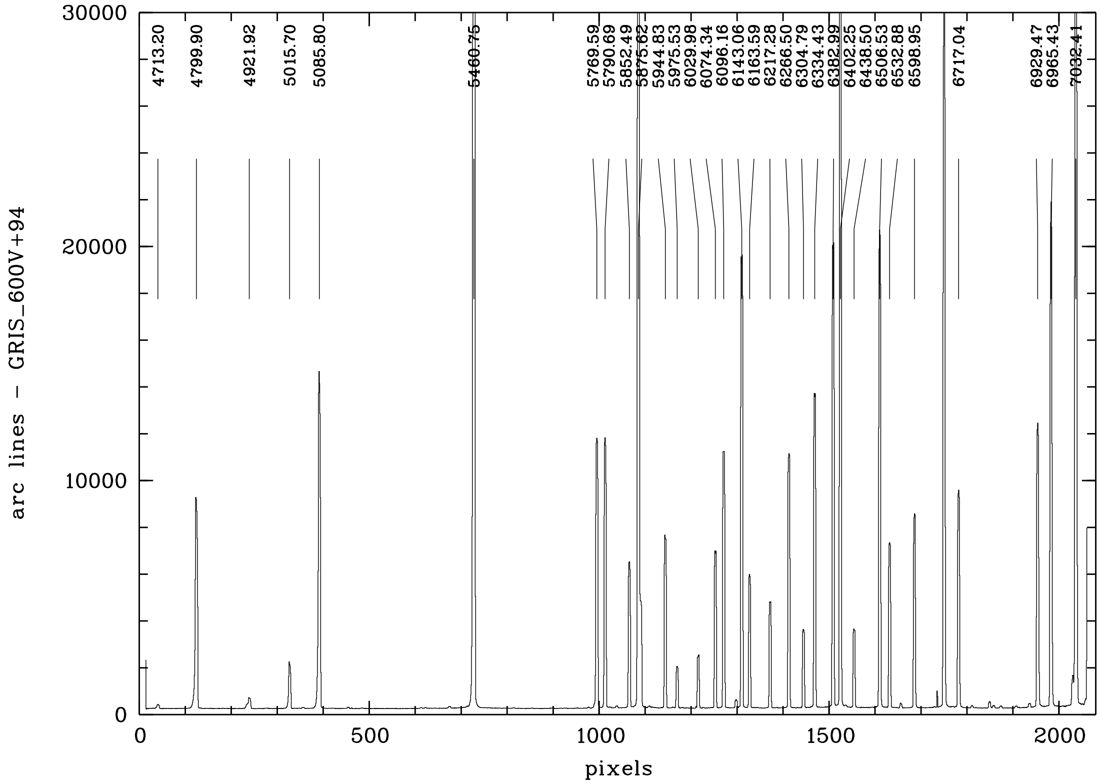

Figure D.7: Calibration spectrum taken with the SR collimator and grism GRIS_600V+94 (FORS1)

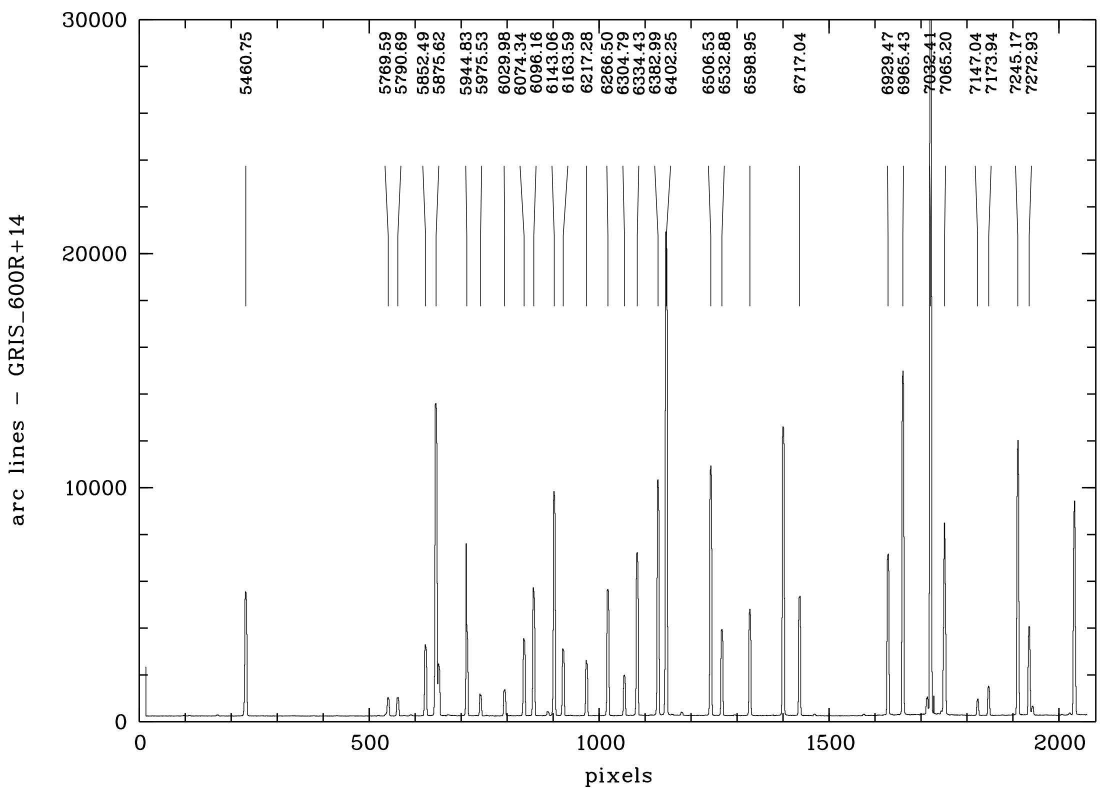

Figure D.8: Calibration spectrum taken with the SR collimator and grism GRIS_600R+14 (FORS1)

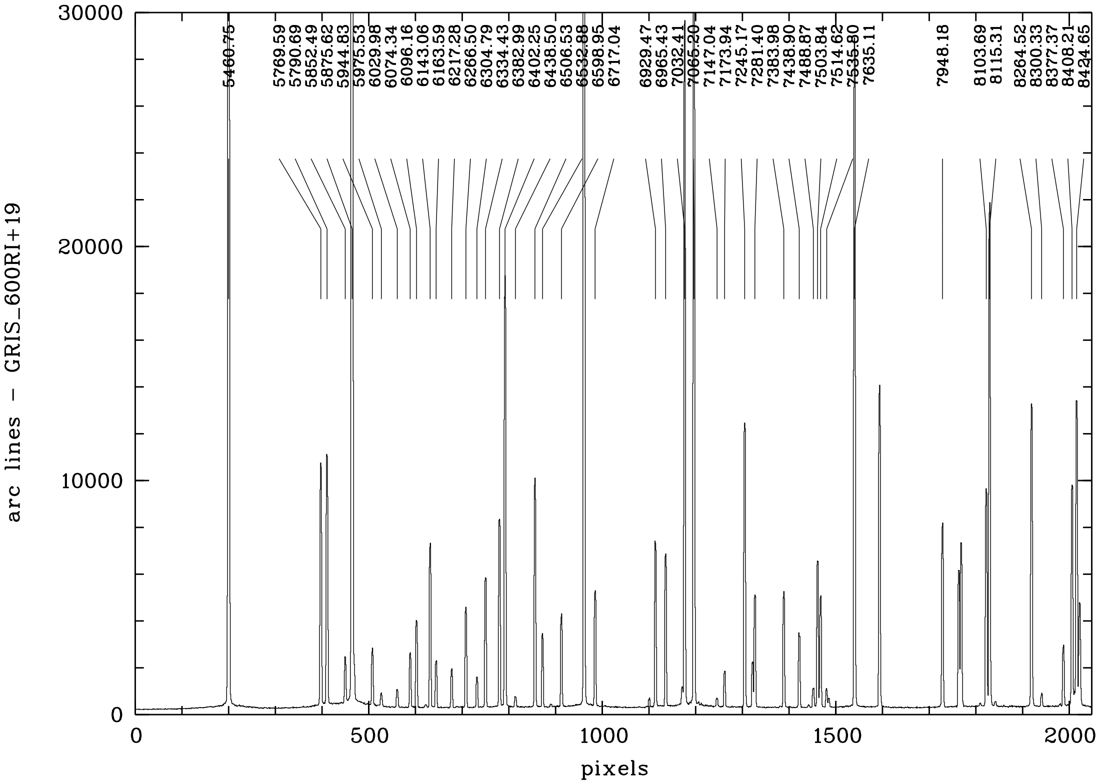

Figure D.9: Calibration spectrum taken with the SR collimator and grism GRIS_600RI+19 (FORS2)

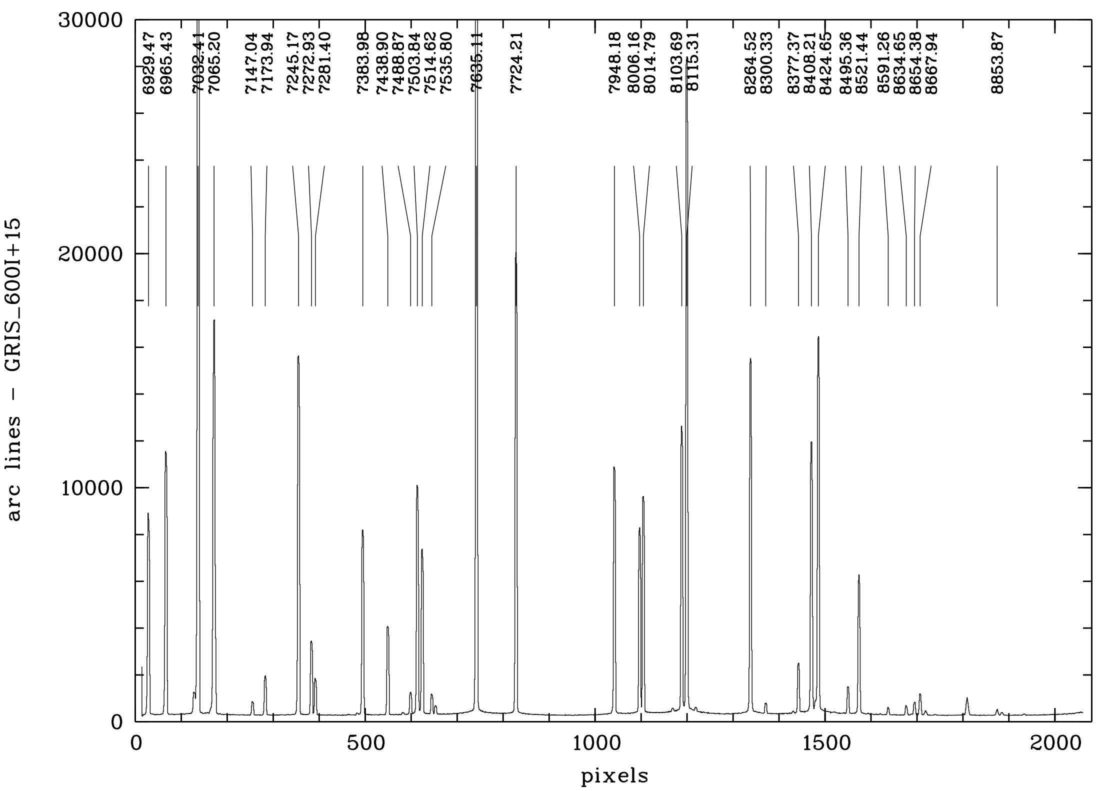

Figure D.10: Calibration spectrum taken with the SR collimator and grism GRIS_600I+15 (FORS1)

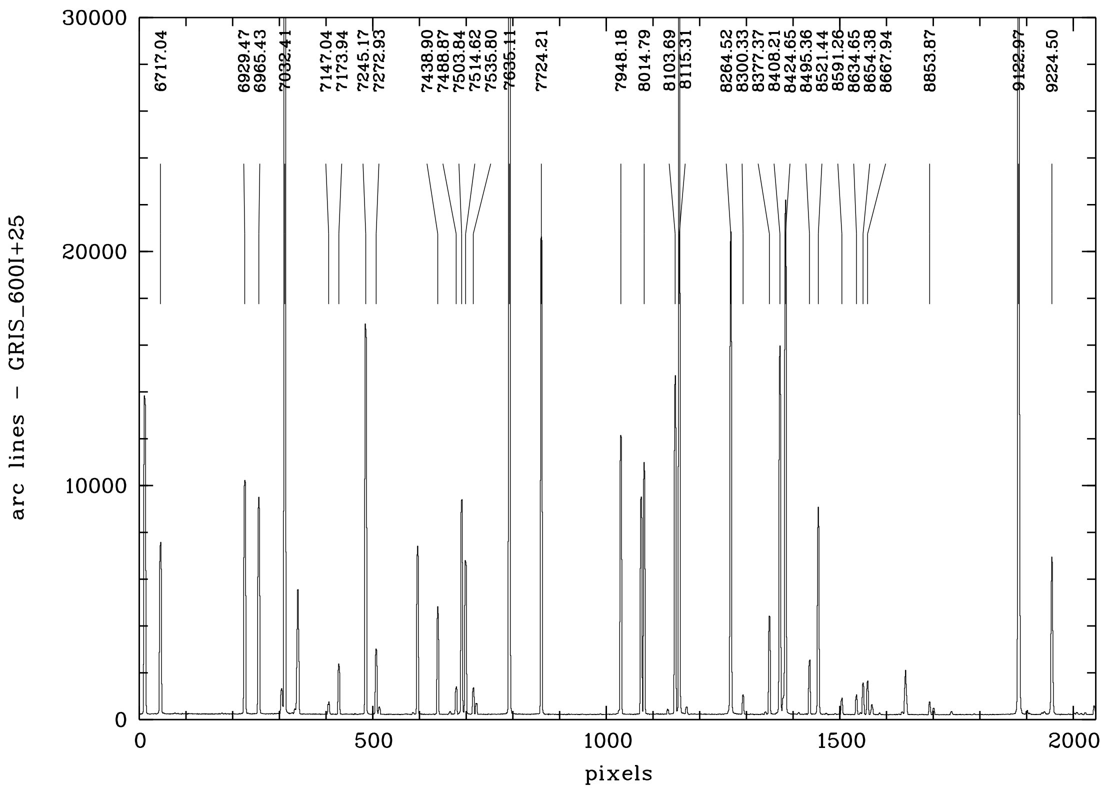

Figure D.11: Calibration spectrum taken with the SR collimator and grism GRIS_600I+25 (FORS2)

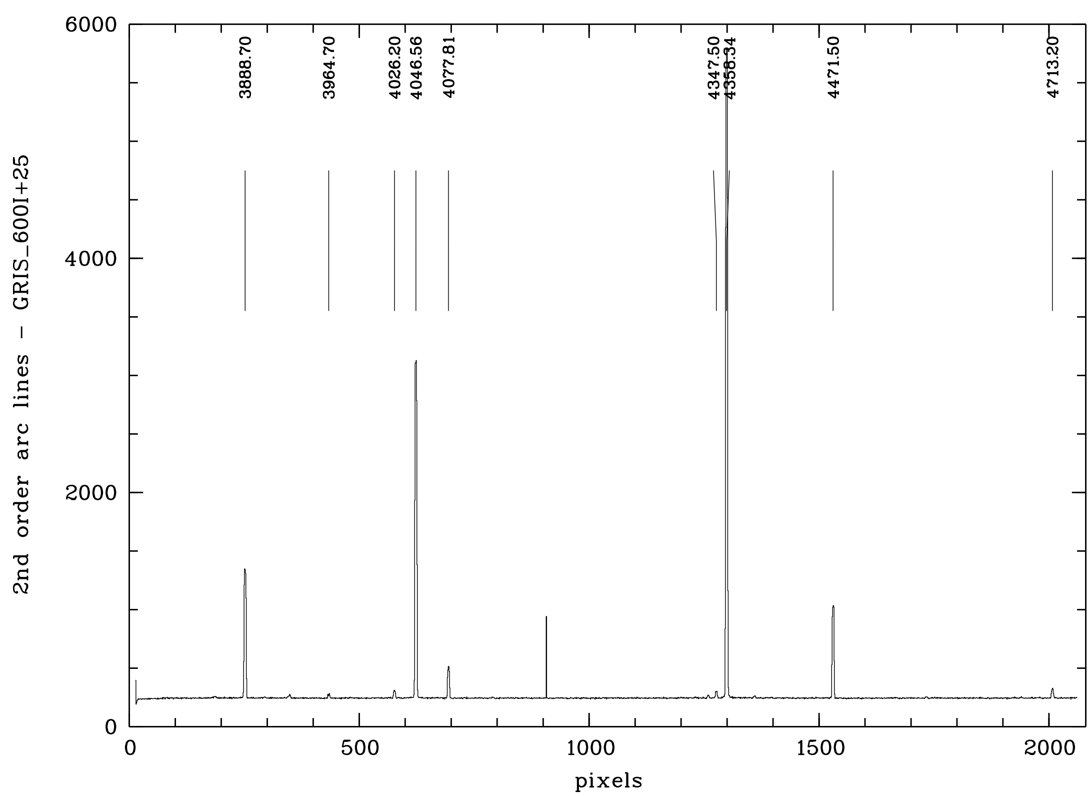

Figure D.12: 2nd order calibration spectrum taken with the SR collimator and grism GRIS_600I+25 (FORS2)

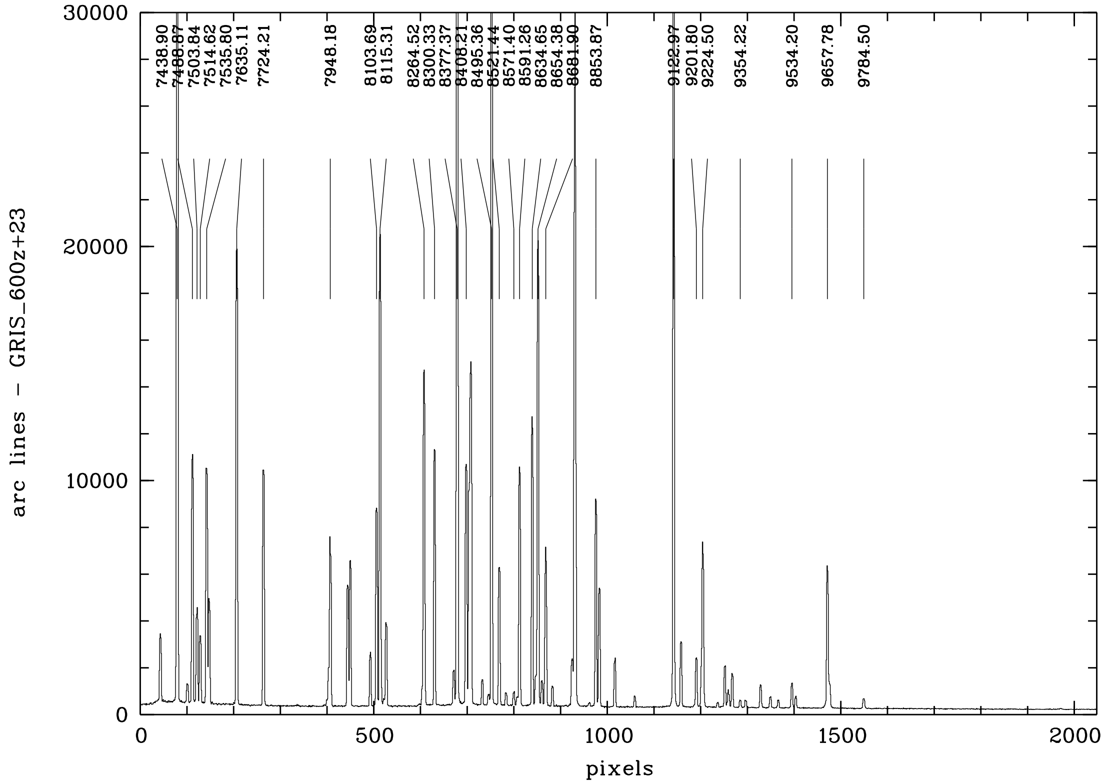

Figure D.13: Calibration spectrum taken with the SR collimator and grism GRIS_600z+23 (FORS2)

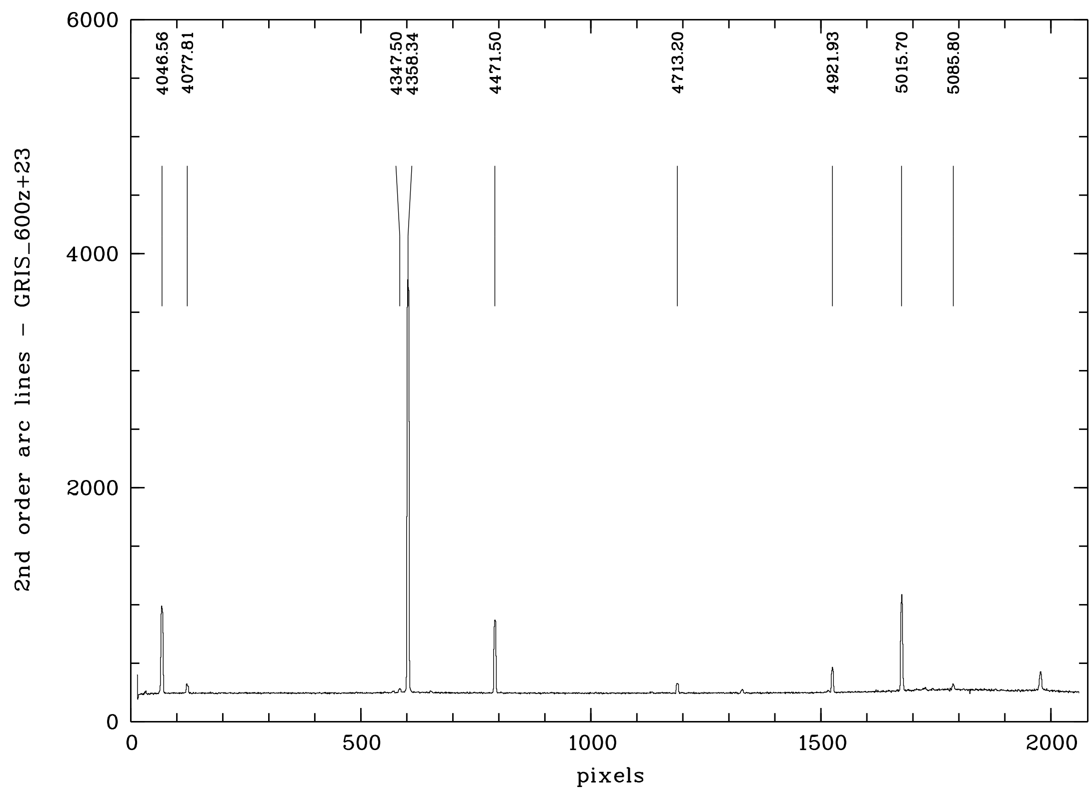

Figure D.14: 2nd order calibration spectrum taken with the SR collimator and grism GRIS_600z+23 (FORS2)

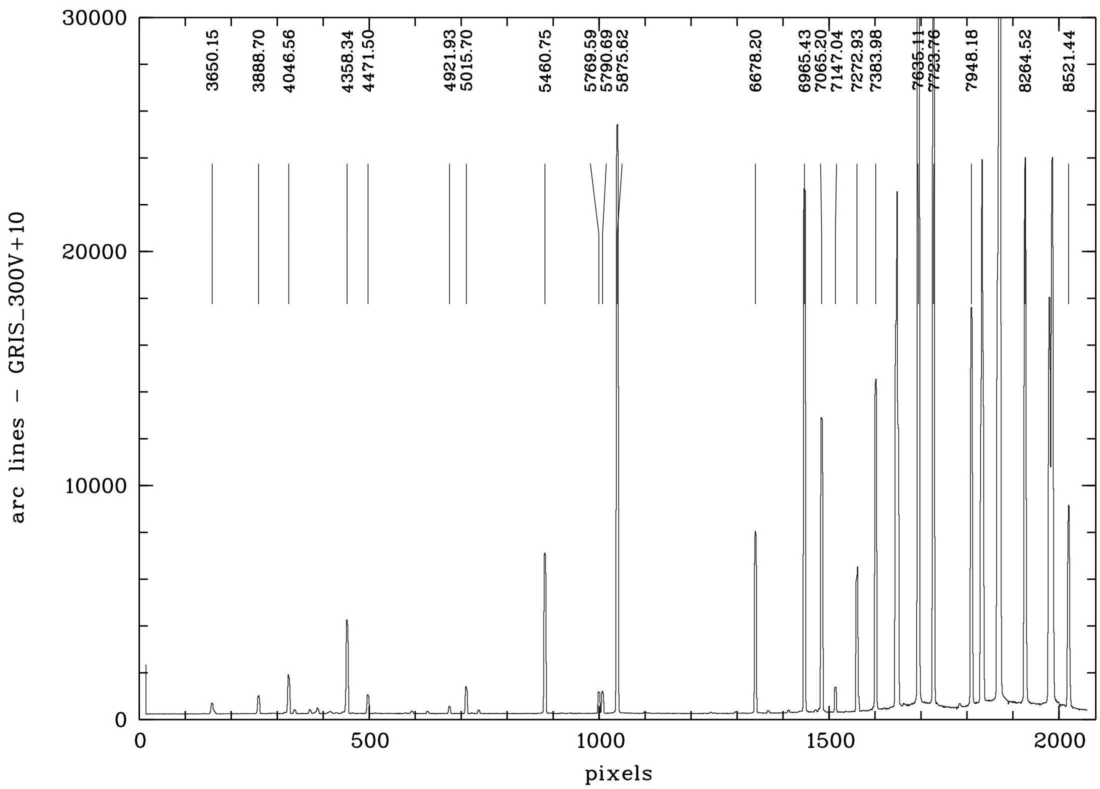

Figure D.15: Calibration spectrum taken with the SR collimator and grism GRIS_300V+10 (FORS1)

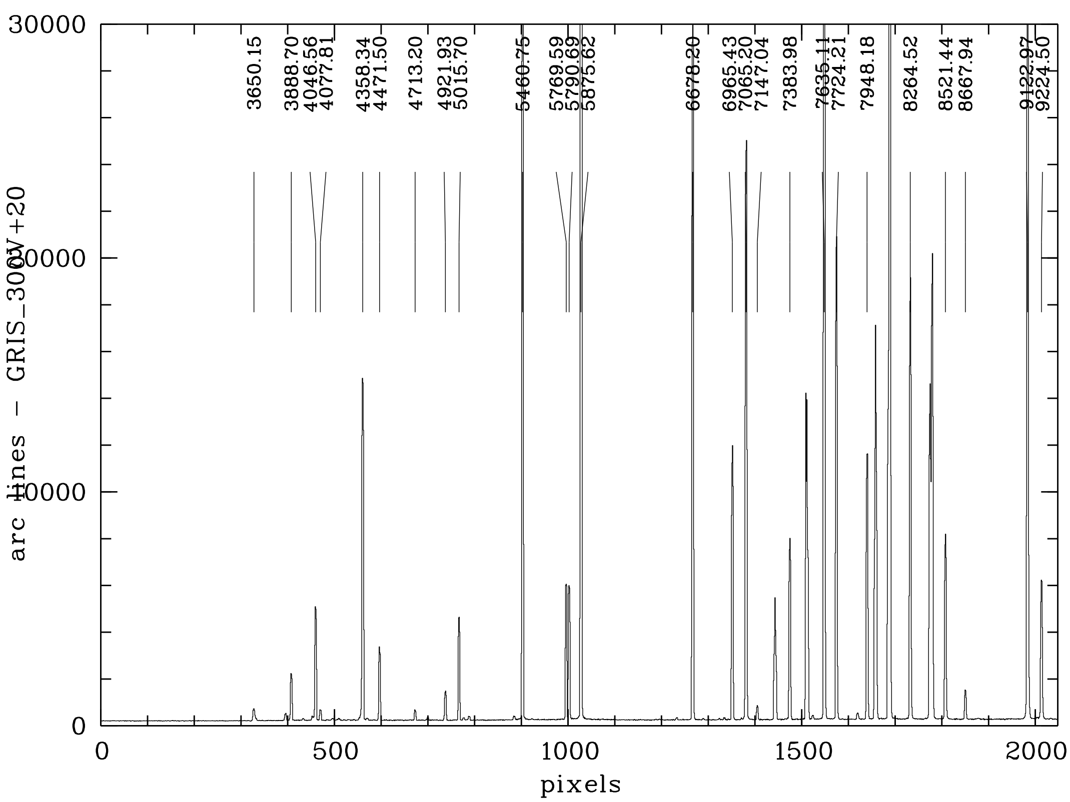

Figure D.16: Calibration spectrum taken with the SR collimator and grism GRIS_300V+20 (FORS2)

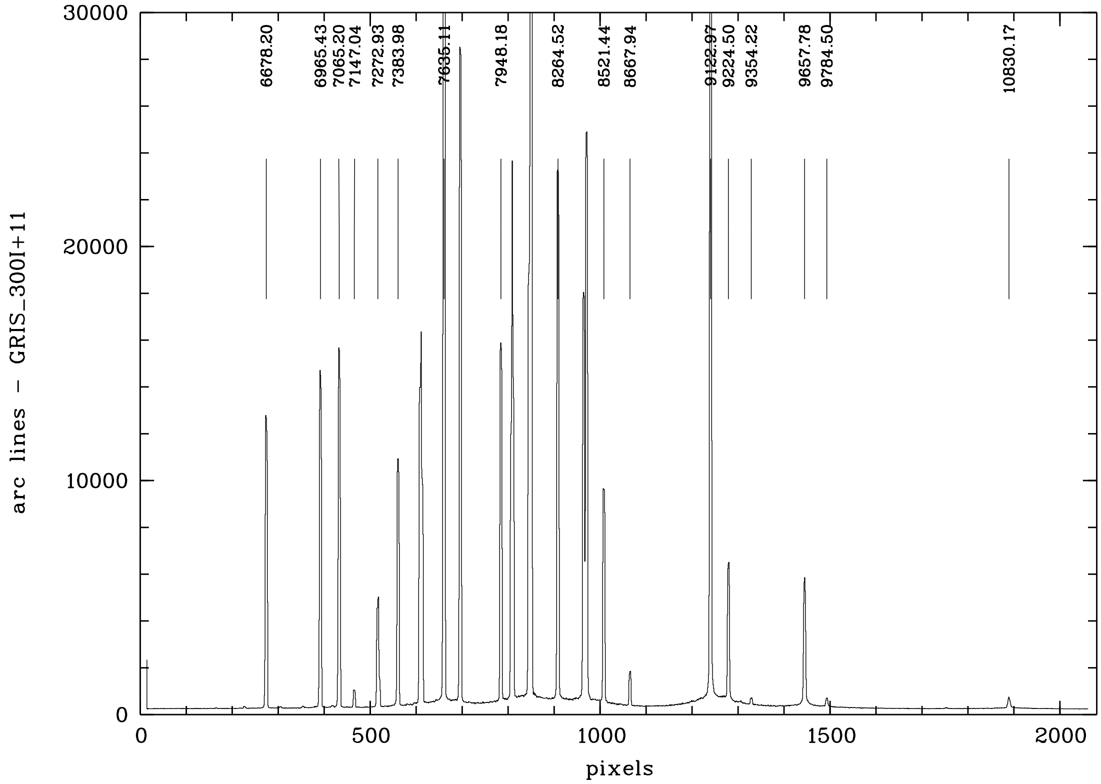

Figure D.17: Calibration spectrum taken with the SR collimator and grism GRIS_300I+11 (FORS1)

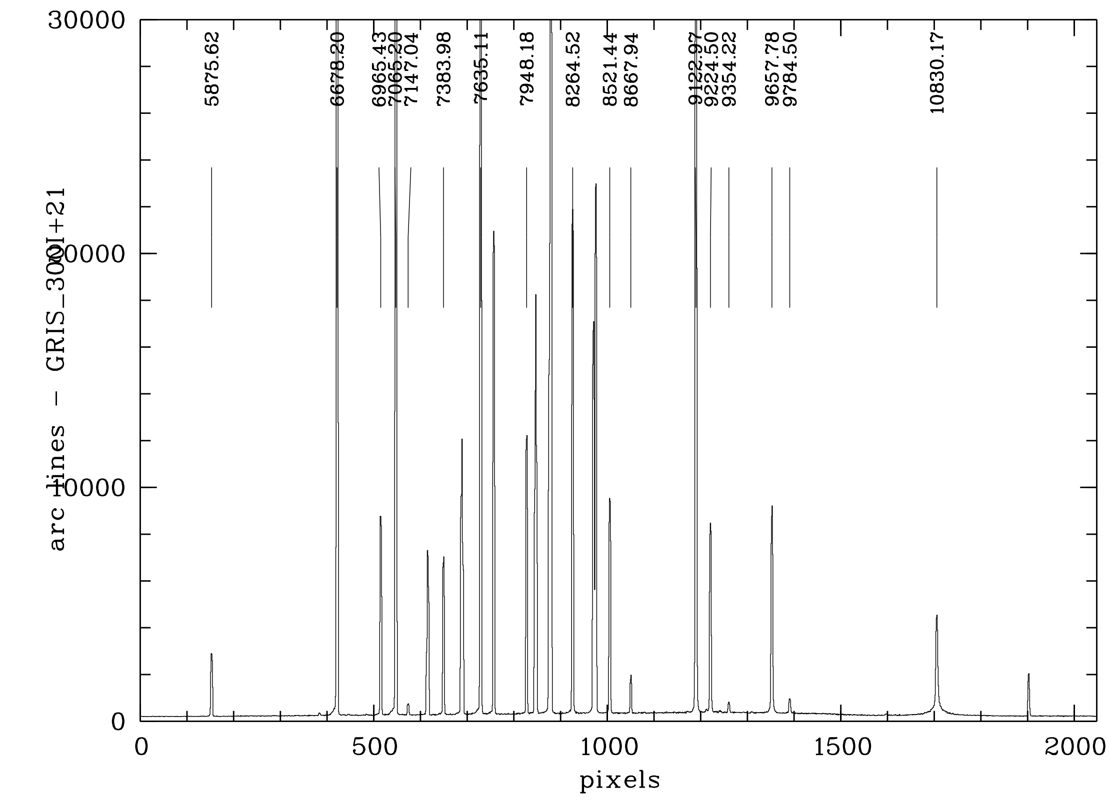

Figure D.18: Calibration spectrum taken with the SR collimator and grism GRIS_300I+21 (FORS2)

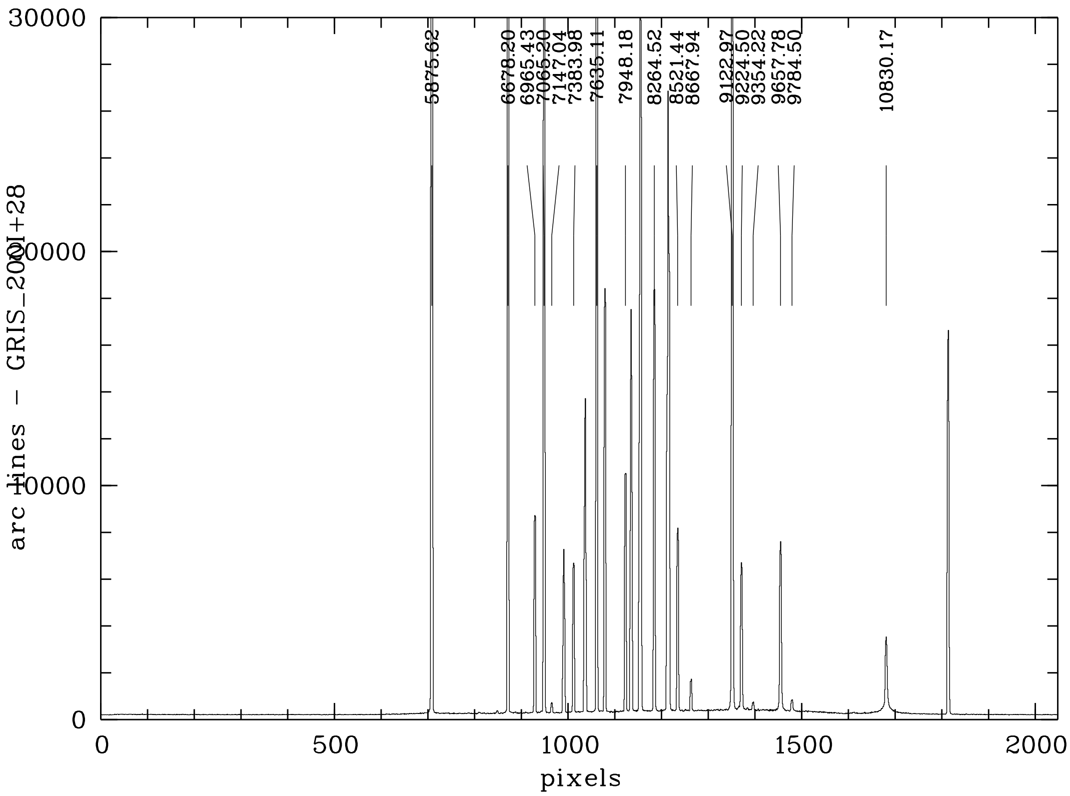

Figure D.19: Calibration spectrum taken with the SR collimator and grism GRIS_200I+28 (FORS2)

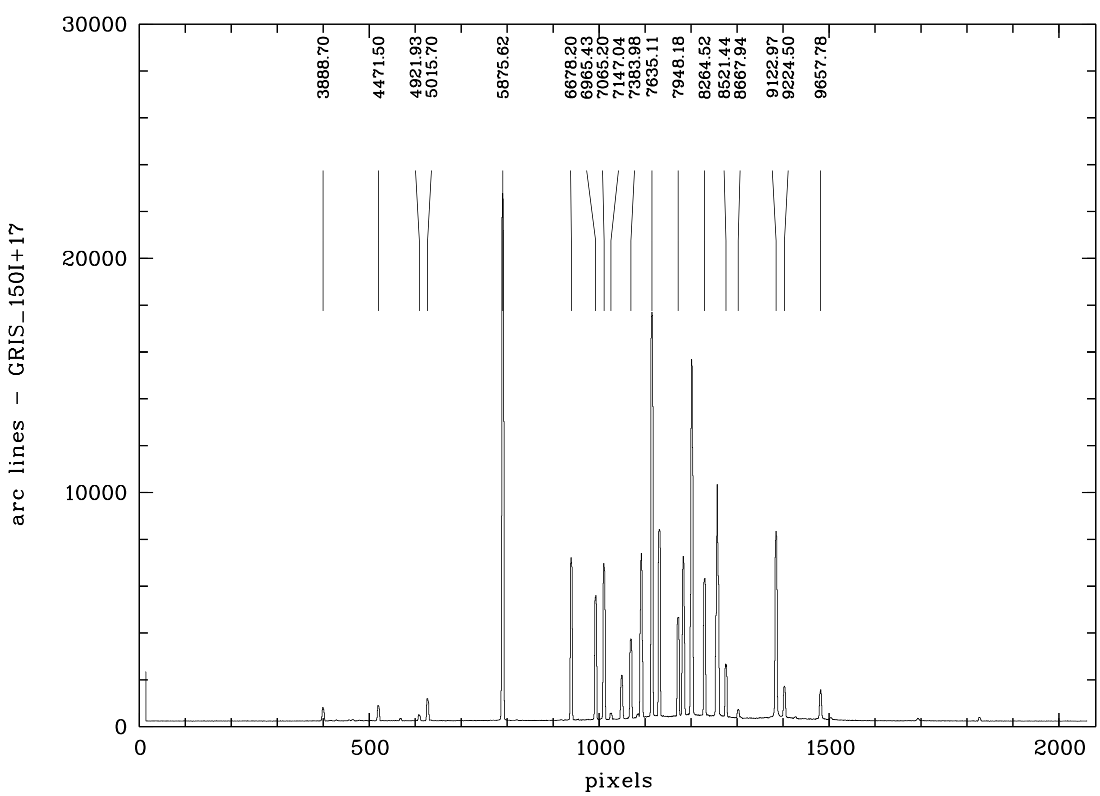

Figure D.20: Calibration spectrum taken with the SR collimator and grism GRIS_150I+17 (FORS1)

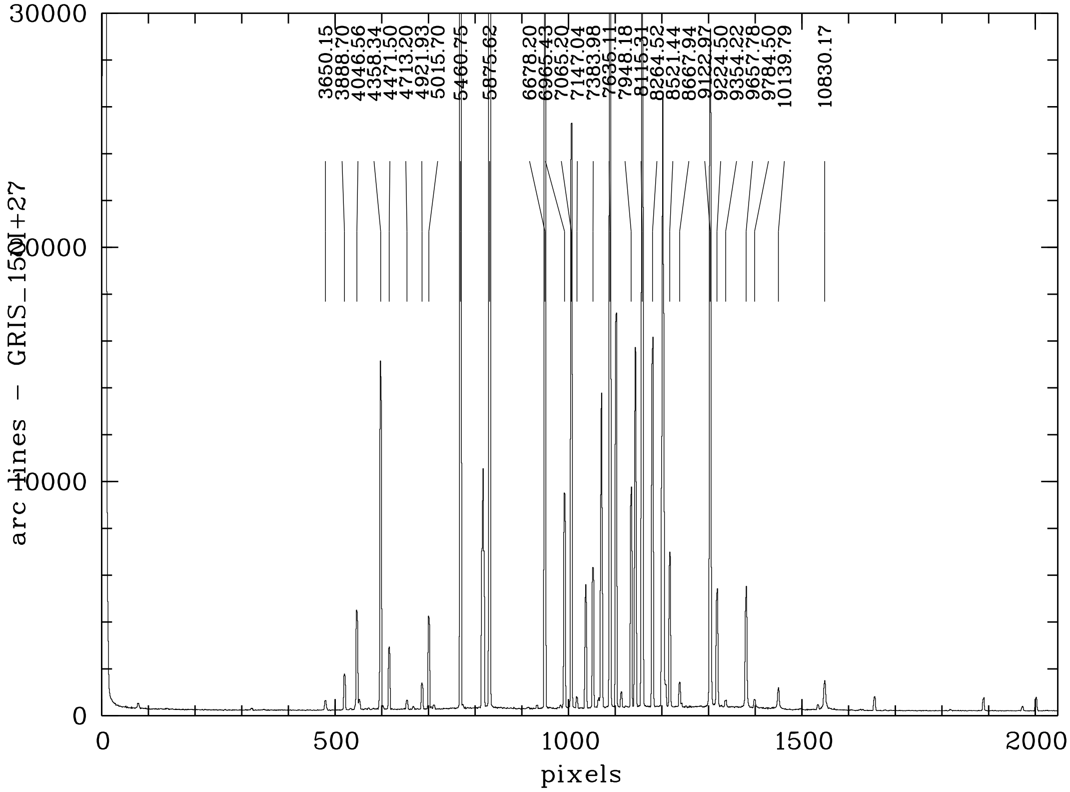

Figure D.21: Calibration spectrum taken with the SR collimator and grism GRIS_150I+27 (FORS2)

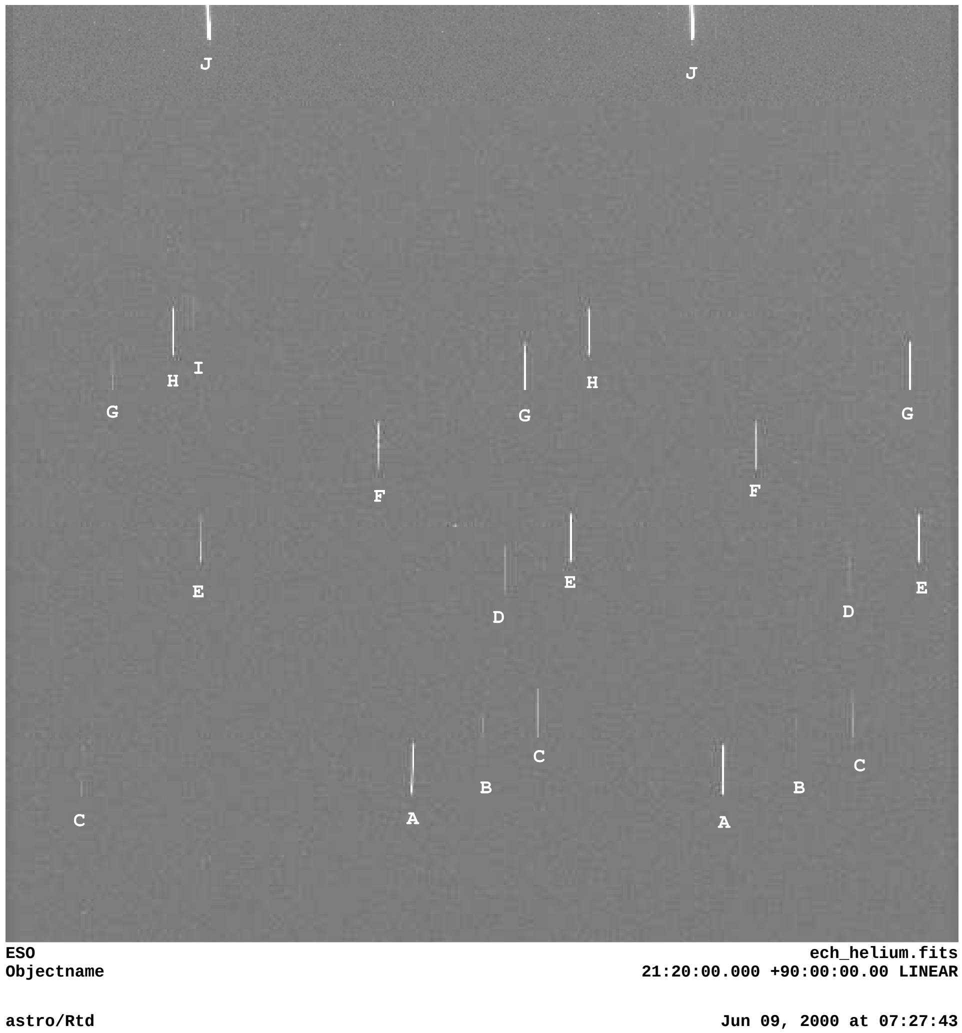

Figure D.22:
Calibration spectrum of the Echelle grism configuration EGRIS_110B+XGRIS_600B taken with the SR collimator and He lamps. Line identification list see Table D.2.

Line ID	Wavelength (Å)
A	3888.6460
B	3964.7290
C	4026.1912
D	4387.9282
E	4471.4790
F	4713.1455
G	4921.9312
H	5015.6797
I	5047.7378
J	5875.6211

Table D.2: Line identification list for Echelle grism configuration EGRIS_110B+XGRIS_600B: HgCd lines see Figure D.23

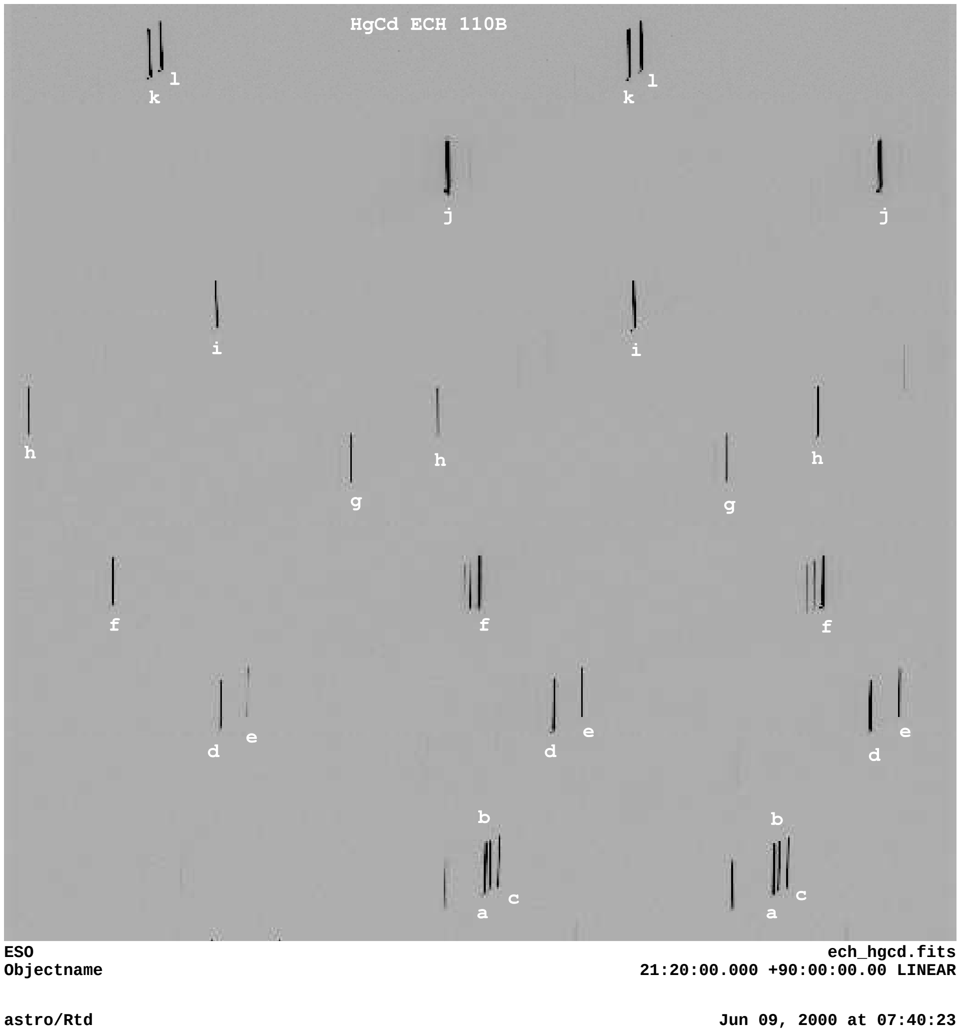

Figure D.23: Calibration spectrum of the Echelle grism configuration EGRIS_110B+XGRIS_600B taken with the SR collimator and HgCd lamps.
Line identification list see Table D.3.

Line ID	Wavelength (Å)
	3610.5000
a	3650.1440
b	3654.8401
c	3663.2739
d	4046.5569
e	4077.8313
f	4358.3428
g	4678.1602
h	4799.9199
i	5085.8242
j	5460.7422
k	5769.5981
l	5790.6558

Table D.3: Line identification list for Echelle grism configuration EGRIS_110B+XGRIS_600B: He lines see Figure D.22

Appendix E

FORS Image Orientation

E.1 MOS Orientation

The orientation of the FORS image in MOS mode is given below for rotator position 0 deg. Note that the sky directions in this schematics change for different rotator angles while the orientation on the CCD remains unchanged. The orientation of the images on the CCD is given in parenthesis. Also given are the locations of the CCD readout ports.

```
   MOS Orientation and CCD Read-out Ports
Rotator angle = 0 (position angle on sky = 0)
---------------------------------------------

                    (TOP)
                 MOS #1, north      pixel 2000,2000
          +-------------------------+
          |C                       D|
          |                         |
          |___                    __|
   MOS A  |___|                  |__|  MOS B
          |                         |
   east   |                         |  west
  (LEFT)  |                         | (RIGHT)
          |                         |
          |                         |
          |                         |
          |                         |
          |A                       B|
          +-------------------------+
  pixel 1,1    MOS #19, south
                  (BOTTOM)
```

E.2 LSS Orientation

The orientation of the FORS image in LSS mode is given below for rotator position 0 deg. Note that the sky directions in this schematics change for different rotator angles while the orientation on the CCD remains unchanged. The orientation of the images on the CCD is given in parenthesis.

```
             LSS Orientation
Roator angle = 0 (sky position angle = 0)
-----------------------------------------
9 longslits in north-south direction

                     (TOP)
                     north          pixel 2000,2000
          +-------------------------+
          |  1.6   0.5   0.4   1.3  | <-slit width in arcsec
          |     \    |   |    /     |
          |      |   |   |   |      |
  (LEFT)  |    | | | | | | | | |    |  (RIGHT)
          |    9 7 5 3 1 2 4 6 8    | <-internal slit number
   east   |    | | | | | | | | |    |  west
          |    | | | | | | | | |    |
          |    | | | | | | | | |    |
          |    |   |   |   |   |    |
          |   /    /   |   \    \   |
          |2.5  1.0   0.3   0.7  2.0| <-slit width in arcsec
          +-------------------------+
  pixel 1,1
                    (BOTTOM)

               Long Slit Decker
               ----------------
                    (TOP)
                    north           pixel 2000,2000
          +-------------------------+
          |       +-+               |
          |       | | <-- LSS       |
          |       | |               |           +-----> x
          |       | |               |           |
          |       | |               |           |
  (LEFT)  |       | |               |  (RIGHT   |
   East   |       | |               |   West    V y
          |       | |               |
          |       | |  +-+          |
          |       | |  | | <-- HIT  |
          |       +-+  +-+          |
          +-------------------------+
  pixel 1,1         south
                   (BOTTOM)
```

The x-distance between HIT decker and LSS decker is half the distance between two LSS slits. If HIT decker enables 0.3'' slit, the LSS decker will enable the large pinhole close to the center of the field of view.

Appendix F

World Coordinate System Information

The header of the FITS file used for preparing a FORS target mask with FIMS should contain the following keywords, for a linear scale:

```
CTYPE1 =         'RA---TAN'     / tangential projection type
CRVAL1 =         12.345678      / x- coord of reference pixel:  RA in deg
CRPIX1 =         512.0          / x coord of reference pixel:  PIXEL
CTYPE2 =         'DEC--TAN'     / tangential projection type
CRVAL2 =         -12.34567      / y- coord of reference pixel:  DEC in deg
CRPIX2 =         525.5          / y coord of reference pixel:  Pixel

CDELT1 =         -3.234E-5      / x- scale:  degrees per pixel
CROTA1 =         10.0           / rot in degrees, from N to E
CDELT2 =         3.234E-5       / y- scale:  degrees per pixel
CROTA2 =         10.0           / rot in degrees, from N to E

EQUINOX =        2000.0         / equinox
```

Beside this conventional CROTA/CDELT-notation there is also the PCiiijjj/CDELT-notation in use, in particular for ESO instruments, where PC keywords are the rotation matrix:

```
CTYPE1 =         'RA---TAN'     / tangential projection type
CRVAL1 =         12.345678      / x- coord of reference pixel:  RA in deg
CRPIX1 =         512.0          / x coord of reference pixel:  PIXEL
CTYPE2 =         'DEC--TAN'     / tangential projection type
CRVAL2 =         -12.34567      / y- coord of reference pixel:  DEC in deg
CRPIX2 =         525.5          / y coord of reference pixel:  Pixel

CDELT1 =         -3.234E-5      / x- scale:  degrees per pixel
CDELT2 =         3.234E-5       / y- scale:  degrees per pixel
PC001001 =       0.9848         / cos(CROTA)
PC001002 =       0.1736         / - sin(CROTA)
PC002001 =       0.9848         / sin(CROTA)
PC002002 =       0.1736         / cos(CROTA)

EQUINOX =        2000.0         / equinox
```

A third notation for WCS FITS header keywords is the CDi_j notation. Transformation formulae between the different keyword notations are given in “A Users Guide for the Flexible Image Transport System (FITS)” (version 3.1, NASA), “Definition of the Flexible Image Transport System (FITS)” (NOST 100-1.2) and the “Data Interface Control Document” (GEN-SPE-ESO-19400-0794).

```
CTYPE1 =        'RA---TAN'    / tangential projection type
CRVAL1 =        12.345678     / x- coord of reference pixel:  RA in deg
CRPIX1 =        512.0         / x coord of reference pixel:  PIXEL
CTYPE2 =        'DEC--TAN'    / tangential projection type
CRVAL2 =        -12.34567     / y- coord of reference pixel:  DEC in deg
CRPIX2 =        525.5         / y coord of reference pixel:  Pixel

CD1_1 =         3.185E-5      / partial derivative
CD1_2 =         -5.616E-5     / partial derivative
CD2_1 =         5.616E-5      / partial derivative
CD2_2 =         3.185E-5      / partial derivative

EQUINOX =       2000.0        / equinox
```

Appendix G

Field vignetting with the FORS2 CCD

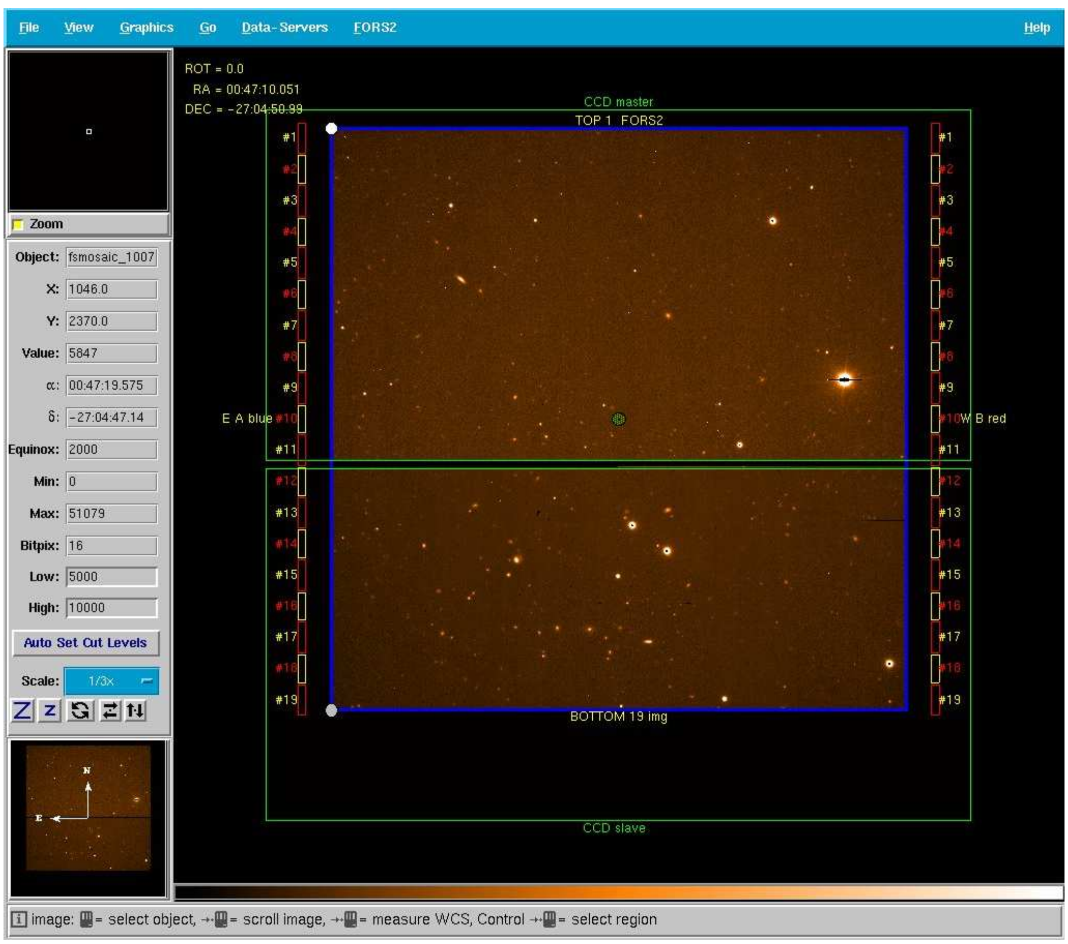

Figure G.1: The field of view of FORS2 with MIT CCDs is restricted by the MOS unit in the focal plane of the unit telescope to about 6.8 arc-minutes for the standard resolution collimator.

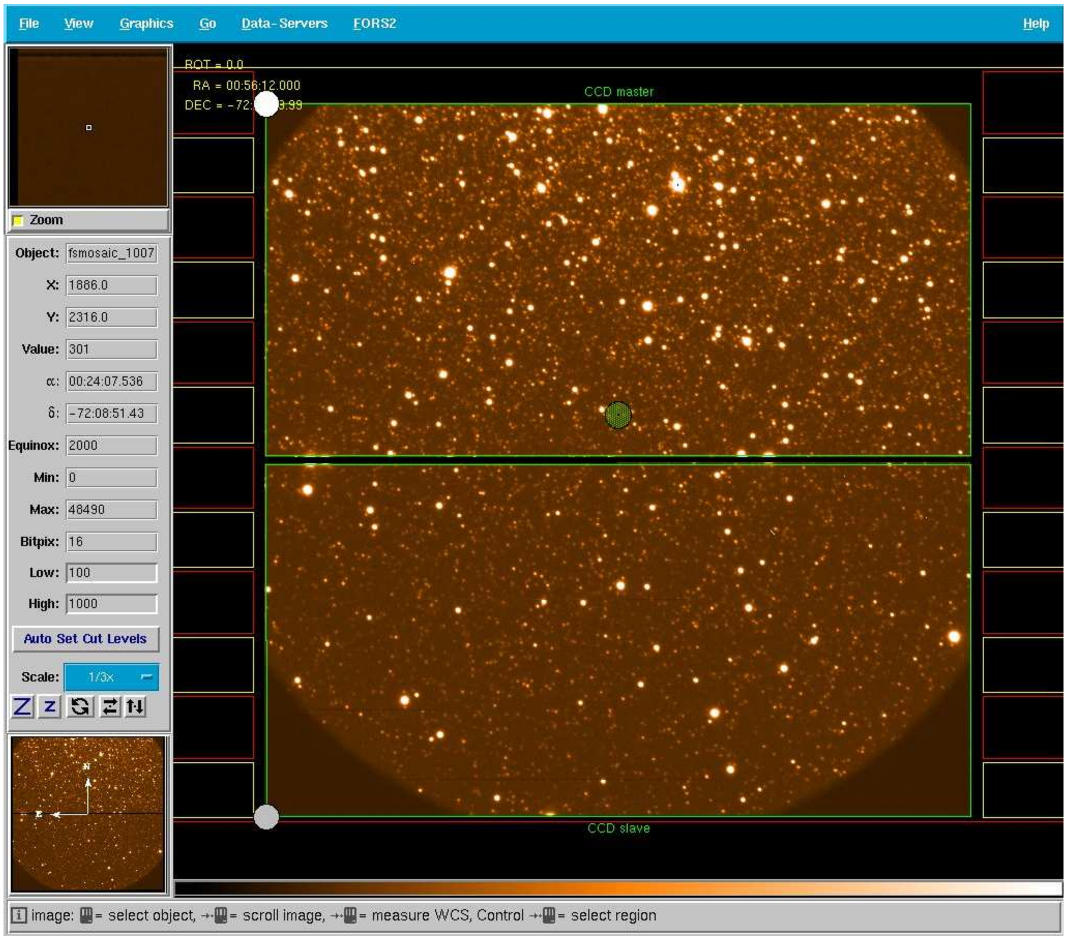

Figure G.2: In case of the high resolution collimator the corners of the field of view are vignetted by the camera lenses.

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