THE FORS INSTRUMENT FOR THE ESO VLT

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1 Understanding FORS

1.1 The FORS Instrument - a short description

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 (standard resolution, SR) resp. 0.1"/pixel (high resolution, HR) on a 2048x2048 pixels CCD detector (pixel size of 24x24 μm). Two versions of FORS are foreseen for the Cassegrain foci of VLT unit telescopes 1 and 3. Table 1 gives an overview of the opto-mechanical instrument hardware which is of importance for the performance of observations. The basic instrument layout is depicted in Figure 1. More details on the opto-mechanical design of FORS can be found in Seifert et al. (1994) and Mitsch et al. (1994).

Mode/Option	Hardware
Direct Imaging	2 collimators 7 broadband filter positions 8 interference filter positions
Spectroscopy	multi slit unit (19 slitlets) 9 longslits 7 grism positions
Polarimetry (FORS I only)	2 phase retarder plates (linear/circular polarimetry) 1 Wollaston prism 1 mask or multi slit unit (for strip mask)
Spectropolarimetry (FORS I only)	combination of equipment for spectroscopy and polarimetry
Optional	6 positions (FORS I) or 7 positions (FORS II) for additional optical components (filters, grisms)

Table 1: Instrument hardware available for astronomical work

The major components are (see Fig. 1 from top to bottom which is top to bottom along the lightpath of the instrument - in parentheses the section designations in Fig. 1 are given): the multi-object spectroscopy unit (A), the two collimator tubes (B and C), the parallel beam section (D) with the phase retarder mosaics, the wheel for the Wollaston prism and optional optical analysers (for instance filters and/or grisms), with the grism wheel and the broadband filter wheel, the camera tube (E), the interference filter wheels (E), the exposure shutter (E) right in front of the CCD dewar (F). Four electronic cabinets are mounted to the collimator section housing (section B - the cabinets are not shown in Figure 1). FORS offers four basic

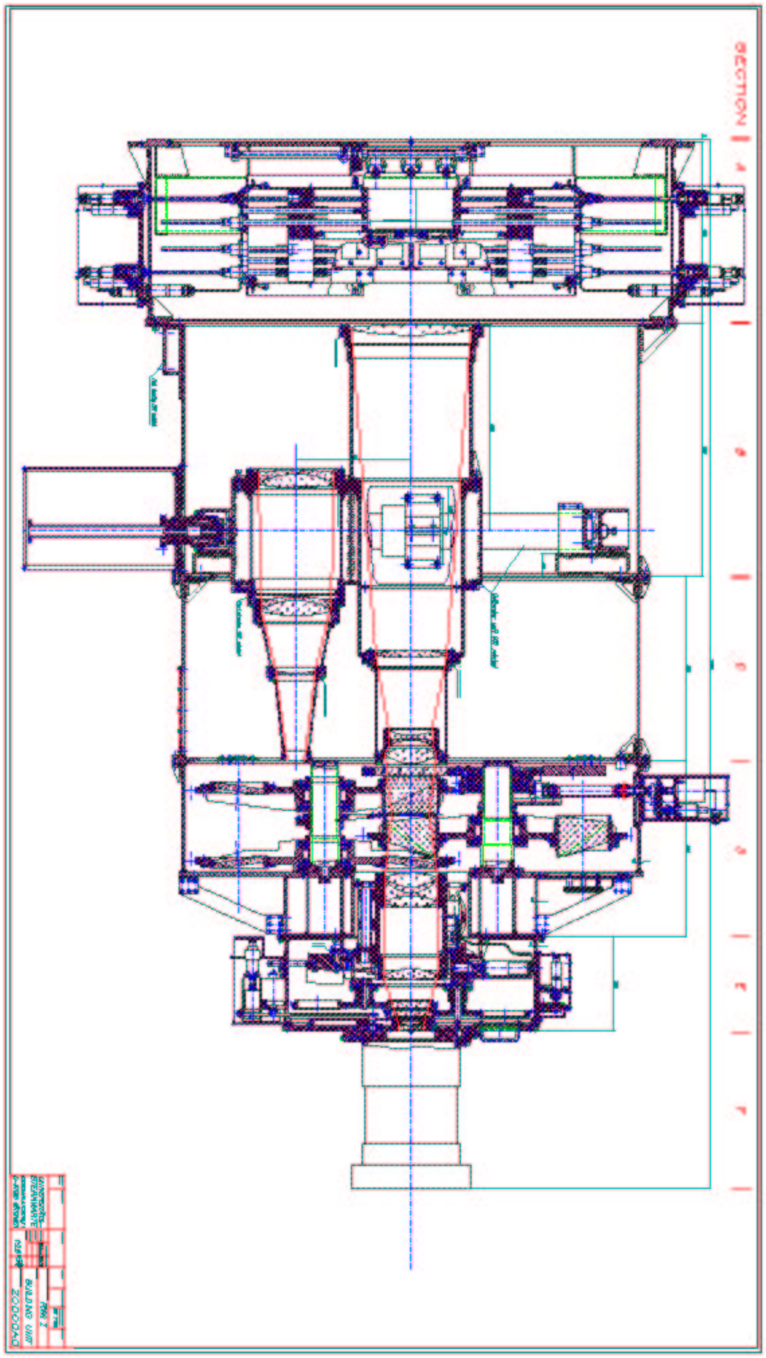

Figure 1: Side view of the FORS instrument

observing modes: direct imaging, spectroscopy, polarimetry, and spectropolarimetry. Each mode contains a variety of observing options which are all permanently installed and easily available for quick "on-line" selection without manual interaction by operations staff.

1.2 Direct Imaging with FORS

The FORS instrument reduces the VLT Cassegrain image scale of 528 μm/" to match the 24 μm pixel size of a 2048x2048 pixels CCD detector. By means of two remotely interchangeable collimators two different

	Standard Resolution	High Resolution
Field of View	6.8'x6.8'	3.4'x3.4'
Pixel Scale	0.2"/pixel	0.1"/pixel
Image Quality	80 % in 0.2"	80 % in 0.1"

Table 2: Predicted performance of FORS in direct imaging mode

Filter	Seeing	Integration Time		
	(")	60 s	600 s	1800 s
U	0.5	25.0	26.5	27.0
	1.0	24.2	25.5	25.9
B	0.5	26.3	27.5	27.9
	1.0	25.5	26.5	26.8
V	0.5	25.8	26.8	27.2
	1.0	24.9	25.7	26.0
R	0.5	25.3	26.3	26.6
	1.0	24.4	25.1	25.3

Table 3: Expected performance of FORS in the direct imaging mode. The table lists the limiting magnitudes for point sources assuming a signal-to-noise ratio of 5, a detector read-out noise of 5 electrons RMS and a calibration accuracy of 0.5 %.

image scales (0.2"/pixel, 0.1"/pixel) can be realized which allow to choose between a wide field for modest (typically 1") and high spatial resolution for excellent ($\leq$ 0.5") seeing conditions. Since the main application of FORS will be very deep ground-based observations the instrument was designed to achieve a superior image quality and high efficiency in the operating wavelength range. The transmission of the FORS imaging optics is: $\approx$ 12 % for a wavelength of 330 nm, $\geq$ 50 % for $\lambda > 355$ nm, $\geq$ 62 % for $\lambda > 360$ nm, maximum of 78 % at 440 nm, and $\geq$ 60 % for λ up to 1100 nm. Table 2 summarizes the capabilities of the FORS instruments in the direct imaging mode for both standard and high resolution collimators.

In standard configuration FORS provides positions for 7 broadband filters in a wheel in the parallel beam section and for 8 interference filters in two wheels in the convergent beam section. Up to 14 additional filter positions are available in the two other wheels in the parallel beam section (grism and Wollaston wheel). Individual arms of the MOS unit can be used in the direct imaging modes as "coronographic masks" to block light from bright objects next to very faint ones. In Table 3 the expected limiting magnitudes in the direct imaging mode through broadband UBVR filters at the VLT are given.

1.3 Spectroscopy with FORS

FORS allows to perform longslit and **M**ulti-**O**bject **S**pectroscopy (MOS). The typical field of view for spectroscopy with the standard and high resolution collimators will be about 6.8'×4' resp. 3.4'×2'. The edges of the field outside this region should be avoided since only a limited section of the whole wavelength range can be used there. In addition the field curvature in the outlying regions of the field will lead to a slight defocussing. As standard option low dispersion spectroscopy by means of grisms is available in both instruments. For FORS II an echelle option is replacing the polarization optics of FORS I.

A main design goal for the FORS spectroscopy modes is high photometric accuracy for very faint objects. Since in the case of such faint objects the observational errors are dominated by the quality of the sky subtraction special care was devoted to achieving appropriate straightness and microroughness of the slitlets (straightness $\leq$ 0.5 μm over 11.5 mm slitlength, microroughness $\leq$ 0.2 μm). In the MOS mode up to 19 objects can simultaneously be observed by means of slitlets which are formed each by two jaws mounted on opposite carriers. The slitlets can be moved by linear guides to any position along dispersion direction in the field of view. The same mechanism allows to continuously adjust the width of each slitlet individually,

Grism	Wavelength range [nm]	Dispersion [Å/mm]	Resolution	Order sorting filters
1	350 - 590	50	815	none
2	525 - 740	45	1230	GG435
3	690 - 910	44	1530	OG590
4	800 - 1030	45	1760	OG590
5	330 - 860	111	420 (500)	(GG435)
6	600 - 1140	108	680	OG590
7	330 - 1100	228	185 (280)	(OG590)

Table 4: Characteristics of the FORS standard grisms. The table lists the resolution achieved for a 1" slit.

Wavelength	dispersion	Integration Time		
(Å)	(Å/mm)	60 s	600 s	1800 s
3600	150	18.3	20.7	21.9
	50	17.2	19.7	20.9
4400	150	19.8	22.3	23.4
	50	18.8	21.3	22.4
5500	150	19.7	22.1	23.2
	50	18.6	21.1	22.3
6500	150	19.4	21.8	22.8
	50	18.3	20.8	21.9

Table 5: Predicted performance of FORS in spectroscopy mode. The table lists the limiting magnitudes calculated for a signal-to-noise ratio of 10 and a seeing and slit width of 1". Detector properties as for Table 3.

and, as a specific feature, individual exposure times for the objects (closing the respective slitlet during the on-going exposure). By combining the linear positioning of the slitlets in the focal area with rotation of the FORS instrument around its optical axis a wide variety of object configurations can be realized. A program will be provided that tries to optimize the number of MOS observations necessary for a given set of objects. The slit jaws have a length of 22" on the sky thus allowing accurate sky subtraction for very faint objects. Prototype tests indicate a reliable performance of the MOS unit during the expected lifetime of the instrument: the absolute positioning accuracy of the slitlets is expected to be better than 8 μm (0.015") with a reproducibility of below 5 μm (0.01"), the slit width accuracy to be better than 10 μm (0.02") with a reproducibility of below 3.5 μm (0.007"). The excellent reproducibility will allow to take calibration data during day time. Further details of the MOS unit are described by Mitsch et al. (1994).

In addition to the adjustable slitlets a mask with 9 longslits is available for the focal area of FORS with a common slit length of 6.8' and fixed slit widths between 0.4" to 1.9". The actual slit for the observation is selected by a decker mask. Alternatively to this mask, a longslit can be set up via the MOS unit inside FORS. The shape of this MOS-longslit, however, is less reproducible than that of the longslit mask due to limited reproducibility of the MOS slitlets.

7 standard grisms are selected to cover the full operational wavelength range of FORS with three different resolutions: 230 Å/mm, 110 Å/mm, 45 to 50 Å/mm (see Table 4). They will be inserted into the grism wheel of the parallel beam section. Order sorting filters or additional grisms can be installed in the broadband filter and/or Wollaston wheels (see below).

While the actual efficiency of the grisms is still under evaluation, the expected performance of low-dispersion spectroscopy with FORS under mediocre seeing conditions is outlined in Table 5 in order to give a first order approximation for observation planning purposes.

For the echelle option in FORS II the Wollaston wheel will be used for the cross disperser grisms. The design of these grisms aims at a dispersion of about 15 to 40 Å/mm.

Filter	Mode	M_{lim}
U	polarimetric	22.1
	spectropolarimetric	15.9
B	polarimetric	23.3
	spectropolarimetric	17.4
V	polarimetric	22.6
	spectropolarimetric	17.3
R	polarimetric	22.1
	spectropolarimetric	17.0

Table 6: Predicted performance of FORS in polarimetric and spectropolarimetric mode. The table lists the limiting magnitudes calculated for imaging and spectropolarimetry of point sources for linear polarization measurements. The limiting magnitudes for circular polarization will be at least as deep with the same total exposure time, since only one Stokes parameter is obtained (on the other hand the amount of circular polarization normally is less than 10 % of the linear polarization). The following parameters are applied: 1 h exposure time, seeing and slit width of 1", dispersion of 50 Å/mm. The signal-to-noise was adjusted to achieve 1 % relative accuracy in the degree of linear and circular polarization. Detector properties as for Table 3.

1.4 Polarimetry and Spectropolarimetry with FORS

A polarimetric mode is foreseen for FORS I only. It allows the measurement of linear and circular polarization, both for direct imaging and spectroscopy. The polarization optics is located in the parallel beam section of FORS and consists of a Wollaston prism for beam separation and two (one each for linear and circular polarization) superachromatic phase retarder plate mosaics (9 individual plates arranged in a quadratic mosaic frame).

Both mosaics are installed in rotatable mountings on a dedicated swing arm which can be moved in and out of the lightpath. The Wollaston prism is inserted in the upper wheel of the parallel beam section.

For imaging polarimetry of extended objects or crowded fields strip masks will be inserted into the focal area of FORS to avoid overlapping of the two beams of polarized light on the CCD. Using the standard collimator the strip mask is formed by placing every second MOS slit jaw carrier arm 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 can be moved into the focal area of FORS.

Spectropolarimetry is possible with the standard collimator for all kind of objects (the MOS slitlet arms are positioned to form alternatingly spectrograph slitlets and "blocking" strips as described for imaging polarimetry). With the high resolution collimator only spectropolarimetry without beam separation mask will be possible, which means that the two beams of polarized light will overlap on the CCD.

The FORS polarization optics shall allow the derivation of the polarization to a relative error of less than 1 % and of the position angle to about 0.2°. The performance of FORS for polarimetric observations is summarized in Table 6.

1.5 Additional FORS features

The instrument design takes care of further features which will be advantageous for the performance of FORS.

Observational performance:

- FORS contains a rotating half-segment exposure shutter which guarantees uniform illumination of the CCD to the 0.2 % level or better for exposure times as short as 1 sec. The shortest possible exposure time is 0.25 sec.
- Finite element analysis for FORS has shown that the image motion due to instrument flexure under gravity will be below 1/4 pixel over a 2 h exposure at elevations above 30 deg (furthermore, an option

for fine-tuning the image motion during the instrument integration tests exists).

- Within typically 20 s the instrument can be switched between the four observing modes. An exchange of the collimators will take about 4 minutes.
- The heat dissipation inside the instrument is below 3 W.

Software services:

- Instrument operation is done via workstation under full remote control (either at the Paranal facilities or from Europe). A simulation mode provided by the instrument related software will allow to prepare and train for FORS observations at ESO Garching and under some circumstances at the user's institute This software will also check whether the prepared observation programme contains all necessary calibration frames and try to optimize the sequence of observations.
- A dedicated and portable software package based on ESO-MIDAS, which is tailored to perform the appropriate data reduction for data obtained in all FORS observing modes, will be provided with the instrument.

Maintenance: The drives and encoders for the moving functions are - with few exceptions - easily accessible from outside of the instrument cover without dismounting the instrument or major parts of it. Modular design and the use of on-line replaceable standardized hardware units shall reduce the demand of maintenance work at FORS.

Direct sky light suppression: Due to the undersized secondary and the lack of baffling direct sky light can reach the Cassegrain focus of the VLT. For FORS observations it is possible to enlarge the M2 silhouette by a retractable ring thus blocking any direct sky light.

2 Testing FORS

Since FORS is still under construction we give a description of all FORS features that will be tested during the assembly and installation of the instrument.

2.1 Checking the FORS performance

The performance of FORS will be tested in different stages of the assembly (in the laboratory, at the **T**elescope and **S**tar **S**imulator (TSS) and at the VLT). The features that will be tested are given below. Results that are of interest for the users will be given in the user manual and also stored electronically if necessary.

- Intrinsic parameters
  - Image scale (0.2"/pixel (SR), 0.1"/pixel (HR))
    At the TSS a target plate with equally spaced pinholes will be placed in the focal plane and observed with FORS in the direct imaging mode.
  - Image quality (80 % encircled energy within 1 pixel)
    The intrinsic image quality of FORS (including filters) will be determined in detail in the laboratory by using an optical set-up which will give a reasonable oversampling of the PSF. At the TSS and the telescope, only checks of the image quality can be made due to the undersampling present with the detector foreseen.
  - Optical distortion
    The optical distortion will be measured using a mask with small holes in known positions. The maximum values of the distortion (at the corners of the field) should be below 0.2 % (SR) resp. 1.5 % (HR). The distortion varies as $\tan^2(\omega)$, where ω is the field angle.
  - Image motion due to flexure (≤ 0.25 pixel)
    The image motion for various zenith distances and azimuth angles will be measured at the TSS using the artificial star.

- Intrinsic transmission of instrument optics
  The values of the intrinsic transmission of the FORS optics given by the manufacturers will be checked at the laboratory.

- Influence on image quality and transmission of grisms, filters, and polarization optics
  Due to the undersampling problems at the telescope all tests of the influence on the image quality will be performed at the laboratory. At the telescope as well as at the TSS only a rough check will be possible.

  - Grisms
    The influence on image quality is derived from the LSF using HeAr lines. To determine a mean value of the grism transmission a point source will be observed with and without grism, using an appropriate filter. Integrating the flux in both measurements will yield the mean transmission. A detailed measurement of the wavelength dependent efficiency of the grisms will be performed in the ESO laboratory.
  - Filters (broad and narrow band)
    To check the transmission curve a spectrum of a continuum source will be taken with and without the filter and the results will be compared. Since the image quality of FORS is defined including filters a test of the influence on the image quality is not necessary.
  - Polarization optics (retarder plates, Wollaston prism)
    For the transmission a source will be observed with and without the polarization optics. To test the influence on the image quality the PSF with and without polarization optics will be compared.

- Polarization optics
  For the polarization optics the data provided by the manufacturers were checked at the laboratory.

  - Effective phase retardation of retarder plates as a function λ for both retarder plates:
    Two Glan-Thompson prisms in the parallel beam section (oriented in parallel for the $\lambda/2$-plate and perpendicularly for the $\lambda/4$-plate) are used for this measurements. The quotient of I_{min}/I_{max} is measured as a function of wavelength. The measurements are performed at different field positions.
  - Position of effective optic axis of retarder plates:
    The position of the effective optic axis varies with the position of the source in the field since different parts of the mosaic contribute for different field positions. The orientation of the polarizers is the same as above for the beginning of the measurement. The plate is then adjusted to the minimum intensity position in one interference filter. The position of the second polarizer where minimum intensity is achieved is recorded as a function of wavelength and field angle.
  - Separation angle of Wollaston prism as a function of wavelength:
    This can most easily be obtained using spectropolarimetric observations of point-sources in different wavelength bands.
  - Effective polarization of Wollaston prism:
    A Glan-Thompson prism in front of the prism is adjusted to minimum intensity successively in both beams. The difference of the prism's position angle should be 90°, independent of wavelength (which is verified). The quotient I_{min}/I_{max} is measured as a function of wavelength.

- Effects of scattered light

  - Sky concentration
    To determine the sky concentration, which should be less than 2 % in the center of the field, a strip mask will be formed by alternatingly opening and closing MOS slitlets and sky flat-fields will be taken. The light level at the areas of the closed slitlet should be a direct measurement of the sky concentration.
  - Ghost images
    The ghost image intensity can easily be determined by observing a bright point source at different field angles. It should be less than 1 % of source intensity for polarimetric measurements and less than 0.01 % for all other measurements.

- Vignetting
  By observing a star cluster at different positions relative to the center of the field vignetting in the field corners can be tested. This is done by comparing the flux of the stars observed in the corner of the field with that obtained for the same stars when they are observed in the center of the field.

2.2 Instrument tests during normal operation

During the normal operation of FORS a test program will exist that allows to check the following features:

- CCD parameters
- Intensity of calibration lamps
- Functional test of instrument hardware, especially moving functions
- Alignment of grisms and Wollaston prism
  The alignment of grisms and Wollaston prism with respect to the CCD rows/columns will be tested and improved until the angle between spectrum and CCD rows resp. the position difference along the x-axis for the two polarization images of a MOS slit lies below some limit.
- Transmission curves of filters
  The tests will compare continuum spectra taken with and without the respective filter. Deviations of the quotient spectrum from a constant will give hints to changes of the filter transmission.

3 Calibrating FORS

Here we give a short overview of the existing data reduction software and describe all kind of calibration data that we think will be necessary for reducing FORS data.

3.1 Data reduction software

In order to keep our **D**ata **R**eduction **S**oftware (DRS) as general as possible for as long as possible we have not yet coded anything specifically for FORS but tried to provide a software that will allow to handle spectroscopic and polarimetric data also from other instruments. Specific FORS features as described below will be dealt with as options of more general commands. At the moment the DRS for the spectroscopic modes (longslit spectroscopy, MOS, and spectropolarimetry) is finished.

It provides for MOS data commands to locate the slitlets automatically and interactively, to perform a flat-field normalization and correction and a wavelength calibration, which will use the known offsets between the slitlets. These offsets will be read from the FITS headers for FORS data or be determined with a cross-correlation algorithm for other data. An algorithm to define object and sky regions automatically (and also interactively if desired) has been developed. For fitting and subtracting the sky-background we are still testing different methods. Various extraction methods are foreseen for the spectra (optimal extraction, simple average, two-dimensional extraction of the slitlets). Rebinning of the spectra to constant wavelength steps will be possible two- and one-dimensionally and also an application of the dispersion relation to one-dimensional spectra without rebinning will be available (creating a table with columns for wavelength position and flux). Flux calibration and extinction corrections will be performed by existing MIDAS commands. Longslit spectroscopic data are treated as a special case of MOS data.

For the spectroscopic reduction of spectropolarimetric data MOS algorithms are used. In addition all observations belonging to one object can be treated simultaneously, using tables created by the Data Organizer package of MIDAS. For the determination of the polarization parameters commands are provided that compute the Stokes parameter spectra and their errors as a function of wavelength and derive the linear polarization and its angle from these parameters (again in the form of spectra as function of wavelength).

3.2 Calibration data that should be available

3.2.1 All modes

For all modes the following CCD data should be readily available at the telescope and also in the FITS headers of FORS files

- read-out noise
- conversion factor
- bias
- dark current
- efficiency
- bad pixels
- linearity

The image motion (size and direction) as a function of zenith distance and rotator position will be stored for a grid of field positions.

3.2.2 Imaging modes

For the direct imaging mode sky flat fields for all filters should be available in a database, that is updated regularly and available via ftp. The distortion as function of field angle will be given in the user manual.

3.2.3 Spectroscopic modes

The alignment of the grisms will be checked after every change and stored in a database (see Section 2.2).

For observations of faint objects the knowledge of the slit illumination pattern for all slitlets (if necessary for various field positions) and longslits is useful. This can be obtained by taking sky flats and averaging them along the dispersion axis.

Since the central wavelength and dispersion of the grisms depend mainly on the slit position they can be evaluated and stored for all longslits. If done with sufficient accuracy this will save the users the time to establish a good wavelength calibration themselves (which can take a considerable amount of time). For the MOS mode these parameters depend on the positions of the slitlets. A map giving the central wavelength and dispersion of the grisms as a function of the positions of the slitlets will be provided.

In case the user decides to perform his/her own wavelength calibration it is very important to ensure that the whole wavelength range is continuously populated by arc lines. This may be difficult to obtain for observations covering a wide range, since arc lines tend to be both more numerous and brighter in the red than in the blue.

3.2.4 Polarimetric modes

The Stokes parameters of the instrumental and the telescope polarization will be given in the coordinate systems of the instrument and the telescope, resp. Since the angles of the instrument and the telescope relative to the equatorial coordinate system will be stored in the FITS header the actual instrumental polarization for each observation can be derived. As the instrumental polarization varies slowly with time a regular update of these values will be necessary. However, for very high accuracy work the observation of standard stars is unavoidable. Since all available polarimetric standard stars are much too bright to be observed with FORS a new sequence should be established (which could easily be done with La Silla telescopes). Regularly updated values of depolarization should be provided.

At certain wavelengths the retardation of the superachromatic retarder plates differs from the nominal value by up to 1% for the $\lambda/2$ plate and up to 3% for the $\lambda/4$ plate, resulting in a wavelength-dependent spurious linear and circular polarization component. This effect is expected to be always negligible for linear polarization measurements. In the case of the $\lambda/4$ plate (at wavelengths where the retardation deviates from $\lambda/4$) linearly polarized light components are not fully converted to circularly polarized radiation, which can result in a non-negligible spurious measured circular polarization of up to several % of the amount of linear polarization. This effect can be well determined and calibrated experimentally by observing the circular polarization of linearly polarized standard stars *provided it is known that these stars have zero circular polarization.* A table with such standard stars will be provided.

The angular offset between the observed and true position angles of the linear polarization measurements and its wavelength dependence must be determined by observing highly polarized standard stars with well known position angles.

The wavelength dependence of the separation angle of the Wollaston prism and of the phase retardation of the retarder plates will be measured and stored and be available by ftp.

3.3 Measurements to ensure constant data quality

To check and maintain the data quality the following measurements should be carried out on a regular base:

Slit illumination pattern: Dust may cause variations of the slit illumination which increase with decreasing slit width.

Intensity of calibration lamps: Aging lamps demand longer exposure times to obtain flat-fields or wavelength calibration frames of sufficient quality. Low S/N calibration data will worsen the data calibration.

CCD data: The CCD parameters like bias, dark-current, etc. should be monitored regularly and the database should not only be updated, but older values should also be kept to allow checks for older data.

Instrumental polarization: The amount and dependence on wavelength of the instrumental polarization may vary slowly with time.

Depolarization: Increased straylight (caused e.g. by dust accumulation on the optics) or undetected (mechanical) defects in the plate rotation drives could lead to an unexpected increase of the depolarization.

Scattered light distribution: The distribution and relative intensity of ghost images may change with new components.

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