Design Benchmarks of the FORS Instrument for the ESO VLT

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Abstract

The visual and near UV focal reducer/low dispersion spectrograph (FORS) for the Very Large Telescope (VLT) offers four basic observing modes: imaging, spectroscopy, polarimetry and spectropolarimetry. A broad variety of optomechanical equipment (i.e. 2 collimators, 7 broadband and 8 interference filters, 7 grisms, 1 Wollaston prism plus 2 retarder plate mosaics for linear and circular polarization, up to 6 optional positions for additional analyser optics, longslit and multi object spectroscopy facilities) are simultaneously installed in FORS and can be utilized by the observer via remote control from a workstation at Paranal or in Europe. Flexible instrument operation for complex observing scenarios with frequent instrument reconfigurations is accomplished by fast motor-driven positioning of the FORS optomechanical components. The instrument performance in the various observing modes is outlined in order to allow potential VLT users to develop a provisional observation planning with FORS.

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 resp. 0.1"/pixel 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 optomechanical instrument hardware which is of importance for the performance of observations. The basic instrument layout is depicted in Figure 1. More details on the optomechanical design of FORS can be found in Seifert et al. (1994) and Mitsch et al. (1994).

The major components are (see Fig. 1 from left to right 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

Mode/Option	Hardware	Details in:
Direct Imaging	2 collimators	Section 2, Seifert et al. (1994)
	7 broadband filter positions	Section 2, Seifert et al. (1994)
	8 interference filter positions	Section 2, Seifert et al. (1994)
Spectroscopy	multi slit unit (19 slitlets)	Section 3, Mitsch et al. (1994)
	9 longslits	Section 3, Mitsch et al. (1994)
	7 grism positions	Section 3, Seifert et al. (1994)
Polarimetry (FORS I only)	2 phase retarder plates (linear/circular polarimetry)	Section 4, Seifert et al. (1994)
	1 Wollaston prism	Section 4, Seifert et al. (1994)
	1 mask or multi slit unit (for strip mask)	Section 4, Seifert et al. (1994)
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

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. In the following benchmarks for the work with FORS are described. They are estimated from the final instrument design, from the properties of already delivered hardware, or from prototype test results.

2. Direct Imaging with FORS

The FORS instrument reduces the VLT Cassegrain image scale of 528 μm/mm to match the 24 μm pixel size of a 2048x2048 pixels CCD detector. By means of two remotely interchangeable collimators two different image scales (0.2"/pixel, 0.1"/pixel) can be realized which allow to choose between a wide field for mediocre (typically 1") and high spatial resolution for excellent ($\leq$ 0.5") seeing conditions. Superior image quality over the field of view and high efficiency of the imaging optics are mandatory for FORS, since the instrument is foreseen to conduct very deep ground-based observations. 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. 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 within the parallel beam section and for 8 interference filters in two wheels within the convergent beam section. Up to 14 further filter positions can be accomplished by a rearrangement of the two other wheels in the parallel beam section. Broadband filters from the Johnson/Bessell and Gunn systems will certainly be available for FORS, while the initial set of interference filters is still under evaluation. Individual arms of the MOS unit (see Section 3) can be used in the direct imaging modes to block light from bright objects next to very faint ones. In Table 3 the FORS performance, i.e. the limiting magnitudes for a given exposure time, in the direct

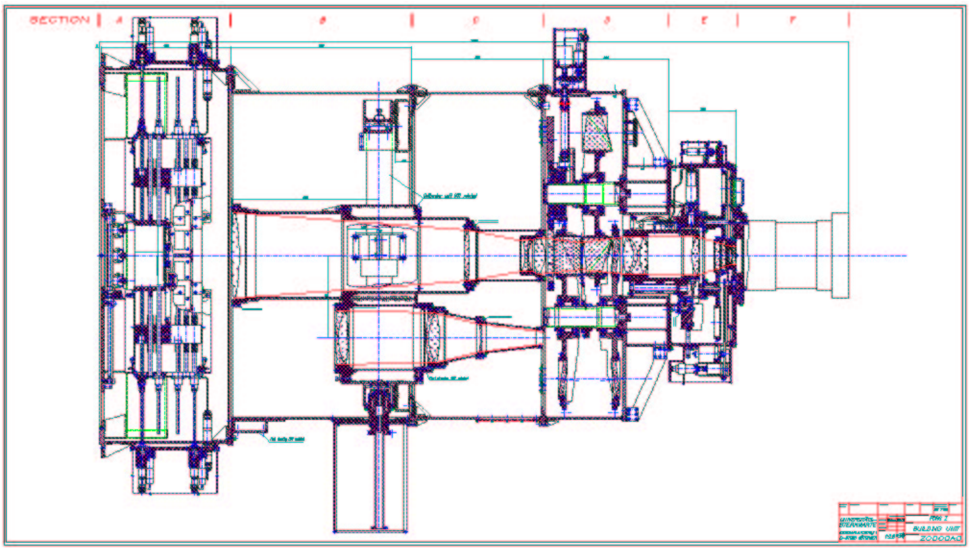

Fig. 1. Side view of the FORS instrument

	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 and Applicable Area	80 % in 0.2” within 4.0’	80 % in 0.1” within 2.0’

Table 2. Capabilities of FORS in direct imaging mode

imaging mode through broadband UBVR filters at the VLT are given.

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’. As standard option low dispersion spectroscopy by means of grisms is available in both instruments. For FORS II an echellette option is foreseen instead of the polarization optics of FORS I.

A main design goal for the FORS spectroscopy modes is high photometric accuracy for very faint objects. Therefore, precaution is applied to achieve appropriate straightness and microroughness of the slitlets (straightness $\leq 0.5\,\mu$m over 11.5 mm slitlength, microroughness $\leq 0.2\,\mu$m). 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. 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, 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

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. Performance of FORS in 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 %.

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 grisms. The table lists the resolution achieved for a 1" slit.

object configurations can be realized. 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 with a reproducibility of below 5 μm, the slit width accuracy to be better than 10 μm with a reproducibility of below 3.5 μm. Further details of the MOS unit are described by Mitsch et al. (1994).

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).

For the echellette option in FORS II the latter 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. 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.

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

Wavelength (Å)	dispersion (Å/mm)	Integration Time		
		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. 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.

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 usual slitlets and strips of the mask required for imaging polarimetry). With the high resolution collimator spectropolarimetry will not be possible.

The FORS polarization optics shall allow the determination of the polarization degree 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.

5. Further Performance Benchmarks

The instrument design takes care of a large number of further features which will become advantageous for the observational, operational, and maintenance performance of FORS.

Observational performance: 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 s (most likely the shortest possible exposure time will be 0.25 s). High positioning accuracy and reproducibility of moving functions was a major design goal: the performance of the MOS unit as described in Section 3 was verified by extensive prototype tests. 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). The heat dissipation inside the instrument amounts to just 2.5 W (while the total power input for FORS is about 1.2 kW). 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.

Filter	Mode	Linear	Circular
U	polarimetric	22.1	22.8
	spectropolarimetric	15.9	17.9
B	polarimetric	23.3	23.6
	spectropolarimetric	17.4	19.5
V	polarimetric	22.6	22.8
	spectropolarimetric	17.3	19.3
R	polarimetric	22.1	22.1
	spectropolarimetric	17.0	19.0

Table 6. Performance of FORS in polarimetric and spectropolarimetric mode. The table lists the limiting magnitudes calculated for imaging and spectropolarimetry of point sources. 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.

Operational performance: Instrument operation is done via workstation under full remote control (either at the Paranal facilities or from Europe). Within typically 20 s the instrument can be switched between the four observing modes.

Maintenance performance: 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.

6. Project Status and Milestones

The two FORS instruments are built under ESO contract by a consortium of three German research institutes: the Landessternwarte Heidelberg, the Universitäts-Sternwarte Göttingen and the Universitäts-Sternwarte München. Principal investigator is Prof. I. Appenzeller (Heidelberg). The FORS project started in December 1991. At present (October 1994), the manufacturing of the FORS I hardware (instrument optics, mechanics, electronics, and telescope and star simulator TSS) is in progress. On the software side the design of major modules for the instrument control is finished and coding was started recently. The FORS data reduction software is about midway to completion (FORS MOS package will be released within the official ESO MIDAS version of November 1994). After a test period of more than one year at the TSS in Europe FORS I is foreseen for installation at the VLT unit telescope 1 in May 1998. FORS II will follow at VLT unit telescope 3 about 16 months later.

7. Acknowledgements

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8. References

Seifert W., Mitsch W., Nicklas H., Rupprecht G., *SPIE Proceedings Series* **2198**, 213-218

Mitsch W., Rupprecht G., Seifert W., Nicklas H., Kiesewetter S., 1994, *SPIE Proceedings Series* **2198**, 317-321