Testing FORS — the First Focal Reducer for the ESO VLT

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ABSTRACT

FORS 1 (**FO**cal **R**educer/low-dispersion **S**pectrograph) is an all dioptric focal reducer designed for direct imaging, low-dispersion multi-object spectroscopy, imaging polarimetry and spectro-polarimetry of faint objects. Two identical copies of the instrument (FORS 1 and 2) are being built by a consortium of three astronomical institutes (Landessternwarte Heidelberg and the University Observatories of Göttingen and Munich) under contract and in cooperation with ESO. FORS 1 and 2 will be installed, respectively, in 1998 and 2000 at the Cassegrain foci of the ESO VLT unit telescopes nos. 1 and 2.

For the tests of FORS in Europe, a telescope and star simulator was built, which allows to incline and rotate the whole instrument and to simulate stars in the field of view at various seeing conditions. FORS 1 was integrated at the telescope simulator and saw its 'first light' in the integration facility in November 1996. Since then the electro-mechanical functions, the image motion due to flexure, the calibration units, the optical performance and the instrument software were tested and optimized. This paper presents a summary of the procedures and the results of the tests.

Keywords: Instrumentation, Optical, Focal Reducer, Testing

1. INTRODUCTION

FORS 1 will be the first instrument provided to the users of the ESO "Very Large Telescope" (VLT) and later on the two instruments will very likely be the most frequently requested instruments of ESO's Cerro Paranal observatory. Therefore, it is very important to test the technical capabilities of the instrument as early as possible, before it is mounted to the telescope in order to assure that good data are produced from the first nights on.

The FORS instruments will have various observing modes, such as imaging with two image scales and spectroscopy at different spectral resolution. Echelle spectroscopy will be possible at FORS 2 and full polarimetric capabilities are provided at FORS 1. For spectroscopy various apertures can be used including longslits and software controlled movable slitlets. Aperture plates will be available with FORS 2 automatically inserted from a storage magazine to the focal plane of the telescope.

We attempted to test all observing modes "in door", before delivering the instrument to the observatory. After the assembling of FORS 1, the instrument was mounted to our telescope and star simulator (TSS), with which we can simulate observations of point sources and extended sources at any position of the sky by tilting and rotating the instrument. In November 1996 the instrument saw "first laboratory light" in the assembly hall. Although some minor problems had to be fixed, it could be established that the optical quality and instrumental flexure properties are excellent and within our design goals.

In Sections 2 & 3 we will briefly summarize the design and the observation capabilities of the instrument. The test facilities will be described in Section 4. The results of the optical tests and flexure measurements are summarized in Section 5 and in Section 6 we will give an outlook to the commissioning tests to evaluate the proper functioning of the instruments at the telescope.

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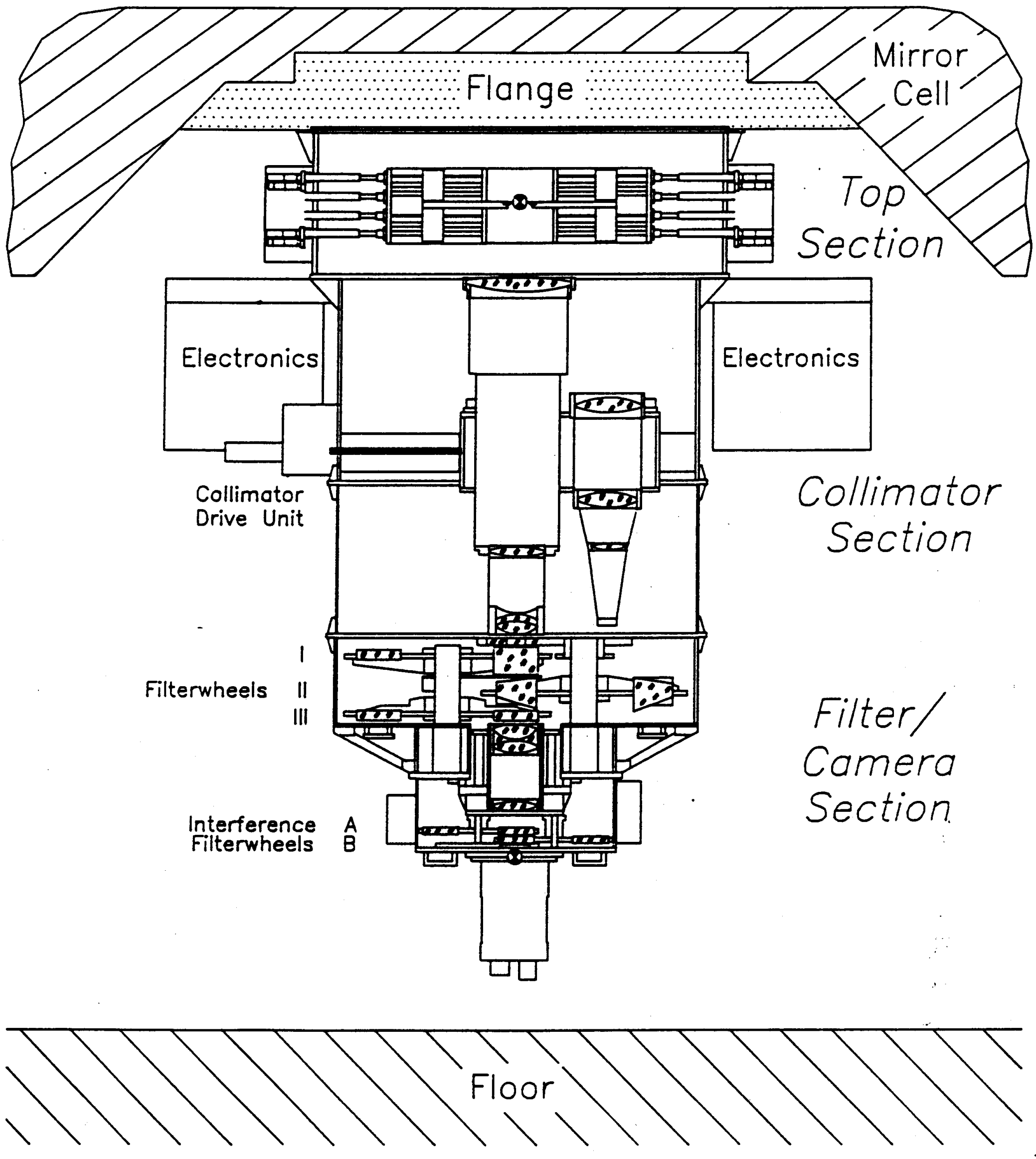

Figure 1. A schematic sketch of the FORS instrument

2. DESIGN OVERVIEW

The FORS instruments consist of three easily separable mechanical sections: the top section with the various apertures, the collimator section with two interchangeable collimators and the filter/camera section with the filters, grisms and the polarization optics followed by the field lens and the detector. See Figure 1 for a schematic overview.

Direct images with the two collimators of a focal length of 616 mm and 1233 mm result in different image scales of $0.1''$ (high resolution) and $0.2''$ (standard resolution) per pixel. Filters can be mounted into two broad band filter wheels in the parallel beam and two interference filter wheels in the converging beam of the camera. The collimators can be easily exchanged at any time under full software control. This allows the observer to react immediately to changing seeing conditions. The field of view will be $3.4' \times 3.4'$ and $6.8' \times 6.8'$ in high and standard resolution mode for the 2K-CCD detector with a pixel size of 24μ.

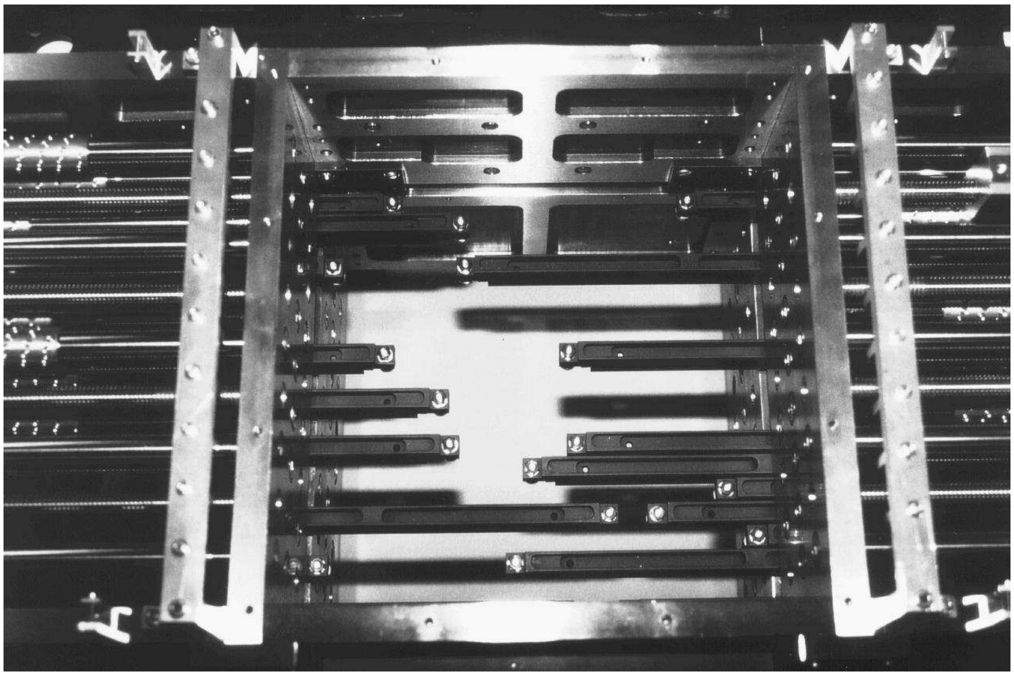

Figure 2. MOS-unit — the 38 slit jaws can be moved to form 19 slitlets in the focal plane of FORS. With the slit jaws one can also form a mask for imaging polarimetry.

Spectroscopy can be done through various apertures. Nine long slits of various slit width are available which are all 6.8′ long projected on the sky to illuminate the detector entirely. For both instruments multi object spectroscopy (MOS) is available with 19 independently movable pairs of slit jaws (see Figure 2). With the slit jaws one can form 19 slitlets centered on the objects with a length of 22″ and any desirable slit width. While this concept has the disadvantage of limiting the object number for MOS to just 19 there are advantages for observations of very faint objects. The slit jaws can be manufactured very smoothly and the slit widths can be adjusted optimally to the seeing conditions during the observations. Therefore and because of the long slit length the sky subtraction can be done in an optimal way.

For applications requiring more slits an additional mask exchange unit (MXU) will be implemented in FORS 2. With the MXU the aperture plates will be inserted from a magazine to the focal plane under software control. Theoretically there is no hard limit for the number of slits in this mode. However for practical reasons the number of slitlets punched into the plate should not be larger than 40 for medium dispersion grisms and 80 for very low dispersion grisms. In the low dispersion case one can think about slits arranged in pairs separated by about 1000 pixels or 3.4′ in dispersion direction. For FORS 2 we will also provide a high resolution spectroscopic mode with echelle grisms and a cross dispersers, to cover the complete visual wavelength range.

FORS 1 will be the first instrument at 8m-class telescopes with full polarimetric observing capabilities. A Wollaston prism can be inserted to the optical axis to split the light into the ordinary beam and the extra-ordinary beam. Stripe masks of 22″ can be formed with the MOS unit to avoid a superposition of the two beams in the case of surface polarimetry. To measure both linear Stokes parameters Q and U at the same position on the CCD, we use a rotatable achromatic half-wave retarder. The circular polarization will be measured with a achromatic quarter-wave plate at the distinct angle of 45° to convert the circular polarized light (Stokes-V) to linear polarized light to be analyzed with the Wollaston prism. As retarder plates of the size of one beam are not available we built 3×3 retarder plate mosaics. The distinct optical axes of the nine individual components of the mosaic are aligned within 0.1°. With the given set of optical components imaging polarimetry and spectro-polarimetry with various spectral resolution will be possible with FORS 1.

Table 1. The FORS 1 schedule - past and future milestones of the instrumentation project

Dec. 1991	contract signature
Feb. 1994	final design
Nov. 1996	first light at simulator
Jun. 1998	shipping to Chile
Sep. 1998	first light at telescope
Jan. 1999	release for observations

FORS 1 has now been assembled and tested. The milestones of our schedule are summarized in Table 1. The manufacturing of the mechanical components of FORS 2 has been started. Principle optical components like the collimators and the camera have been delivered and tested in the laboratory. These components are identical to the FORS 1 optics. The second instrument is scheduled to be released for observations on UT 2 in April 2000, with the mask exchange unit (MXU) and the high spectral resolution grisms.

3. INSTRUMENT PERFORMANCE AND TRANSMISSION

The transmission of the actual FORS optics was derived from the laboratory measurements of the individual components. Collimators and cameras are included in the calculation of the overall transmission which is 77 per cent at peak wavelength and greater than 57 in the wavelength range from 370nm to 1100nm. The transmission curve is very smooth (see Table 2). For very short wavelengths below 370nm the transmission decreases strongly because of the UV absorption of the glass. The instrument alone would be also efficient in the near infrared range but the CCD-detector used with FORS will limit the instrument performance strongly to wavelengths above 900nm.

Apart from imaging, the longslit and multi-object spectroscopy is expected to be the most frequently requested observing mode with FORS. Various grisms are provided to obtain spectra at various wavelength ranges and any spectral resolutions. For a $1''$ slit the resolution $\lambda/\Delta\lambda$ will be between 200 and 1700 at FORS 1 and up to 3000 in Echelle mode at FORS 2. More details are given by Fürtig & Seifert 1995.[1] Table 3 and Figure 3 summarize the optical parameters of the grisms. The wavelength range is given for a slit in the center of the field of view and the CCD detector of FORS 1. Grisms 5 and 7 can be used in the red only in combination with an order separation filter. An additional grism for very low resolution observation blazed in the red is on order.

Table 2. The efficiencies excluding the CCD of the two instruments for the two collimators (HR: high resolution — SR: standard resolution).

λ	FORS 1		FORS 2	
[nm]	SR	HR	SR	HR
330.0	0.107	0.087	0.113	0.086
340.0	0.300	0.284	0.308	0.283
350.0	0.465	0.455	0.475	0.456
370.0	0.659	0.670	0.669	0.675
400.0	0.751	0.768	0.761	0.775
500.0	0.742	0.766	0.749	0.776
600.0	0.676	0.707	0.683	0.716
700.0	0.632	0.659	0.642	0.666
800.0	0.604	0.630	0.614	0.635
900.0	0.588	0.616	0.596	0.621
1000.0	0.578	0.609	0.584	0.614
1100.0	0.570	0.601	0.575	0.606

Table 3. The FORS grisms for low and intermediate spectral resolution observations

Grism	glass	gr/mm	ϕ	λ range	dλ/dx	$\lambda/\Delta\lambda$
				nm	Å/mm	
1	FK 5	600	34°	350 ... 590	50	815
2	K 5	600	46°	525 ... 740	45	1230
3	SF 5	600	46°	690 ... 910	44	1530
4	SF 11	600	46°	800 ... 1030	45	1760
5	FK 5	300	21°	330 ... (650)	110	420
6	LF 5	300	26.7°	600 ... 1140	108	680
7	BaK2	150	11.5°	330 ... (650)	225	185
GG 435 & 5				(450) ... 860	112	500
OG 590 & 7				(590)...1100	230	280

ϕ: prism angle — the spectral resolution $\lambda/\Delta\lambda$ is given for a 1″ slit

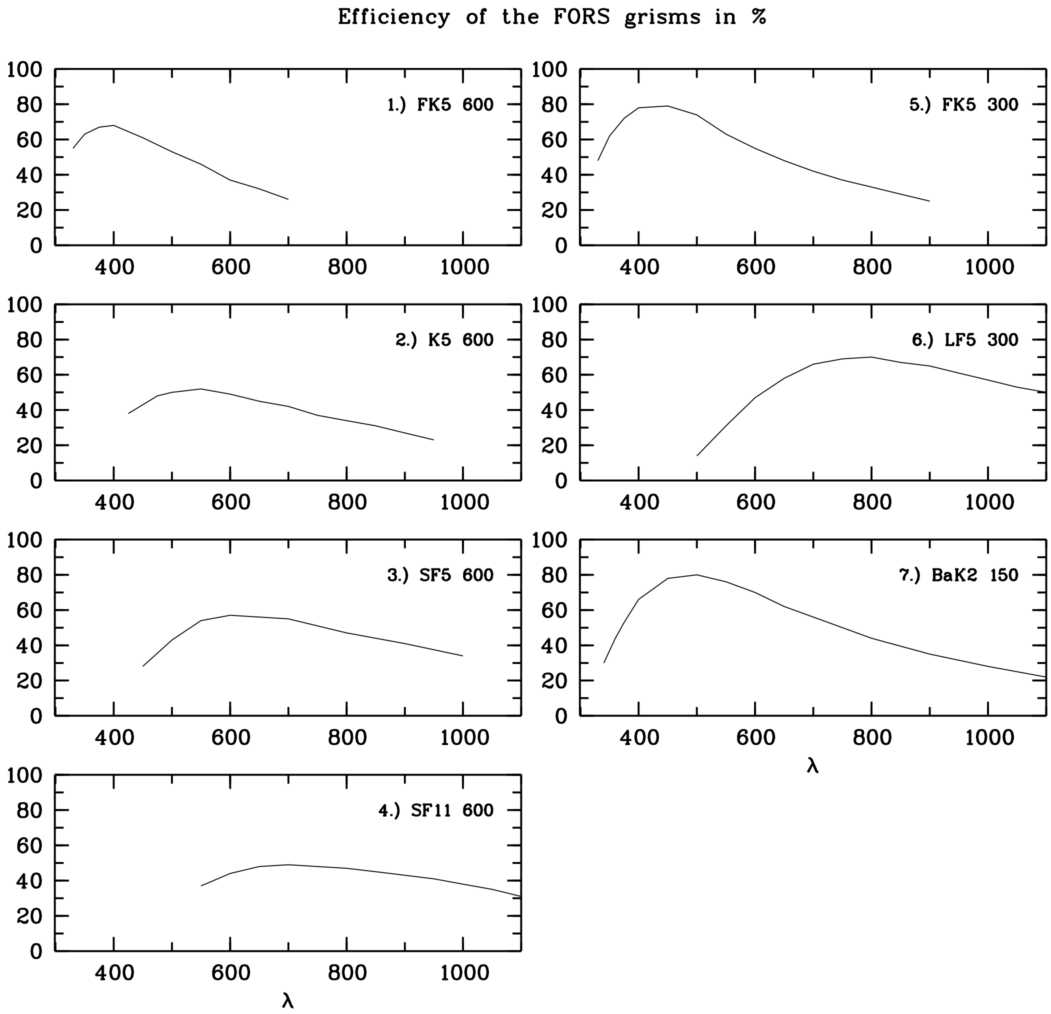

Figure 3. Efficiency of the various FORS grisms in per cent. The use of grisms 5 and 7 in the red requires order separation filters.

4. TELESCOPE AND STAR SIMULATOR

The test facility consists of two components: the telescope simulator and the star simulator. The telescope simulator is a mechanical structure which allows to tilt the instrument around a horizontal elevation axis. Any position of the instrument at the sky can be simulated by rotating the the instrument flange. Figure 4 shows the FORS 1 instrument mounted to this test facility. More informations about the telescope simulator is given by Nicklas et al. 1997.[2]

The star simulator consists of a light source and simple optics to simulate the incoming light beam of a point source with the same focal ratio as the telescope. The device is movable to reach any point of the focal plane. It is also possible to simulate the curved focal plane of the VLT by moving it parallel to the optical axes. FORS corrects for the coma of the VLT telescope in the Cassegrain focus. As this cannot be simulated by the star simulator, the tests of the off-axis image quality cannot be performed accurately.

Various other tests can be carried out with the test facility: Flexure measurements can be done with internal pinholes mounted in the top section of the instrument and with an external pinhole which guarantees measurements independently from the internal structure of FORS. The star simulator can be replaced by a calibration screen, to test the FORS calibration units, which consist of an optical projection system and various light sources for flat field and wavelength calibration. This screen is at the same distance from the focal plane as it will be at the telescope.

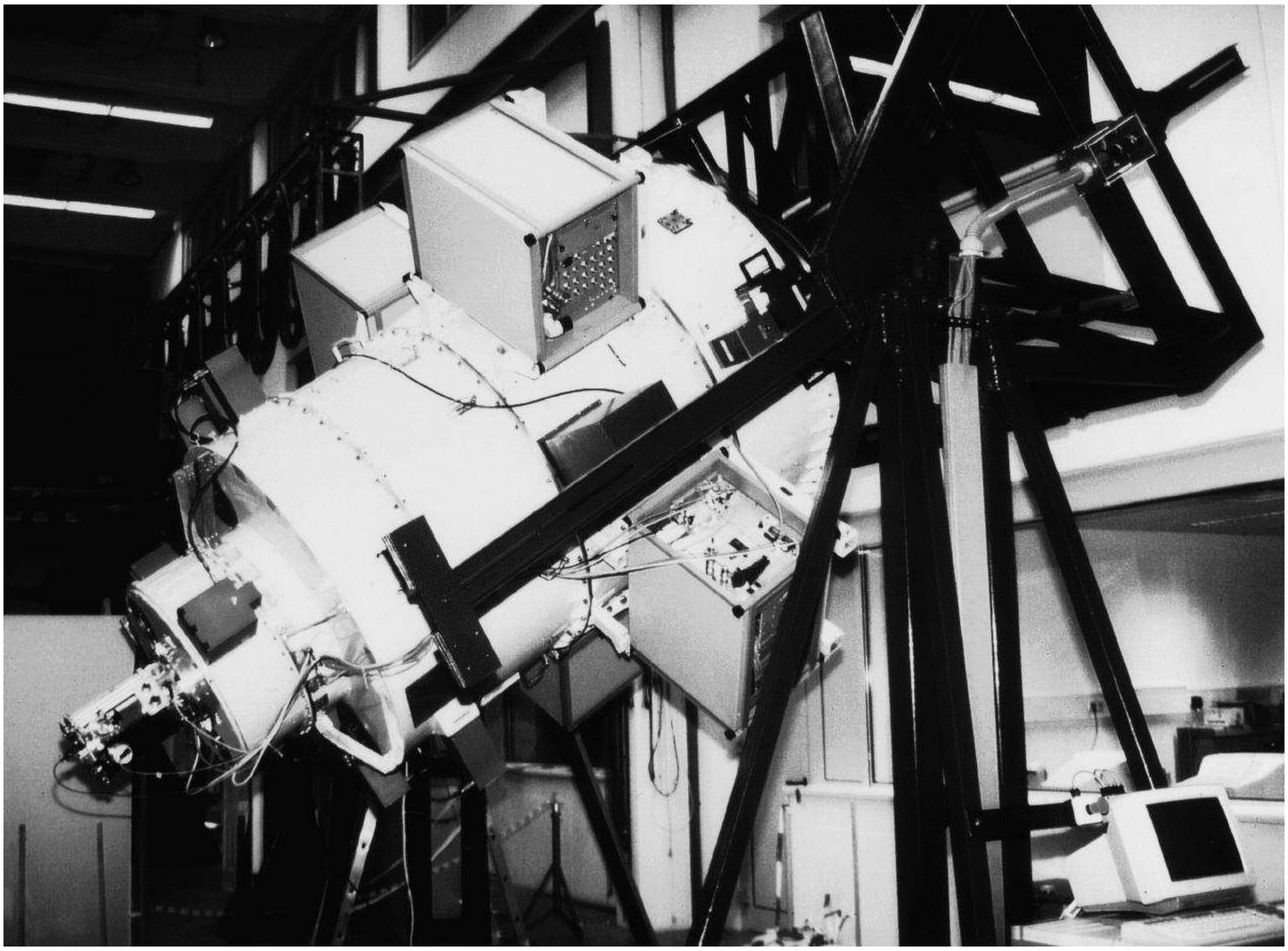

Figure 4. FORS mounted on the telescope and star simulator during first flexure tests

5. TEST RESULTS

The first laboratory measurements were made on an optical bench mainly to check if the optical components fulfill the specifications. Some test measurements can be done in the laboratory more precisely: The image quality measurements of the completely assembled instruments are restricted by the large size of the CCD-pixels compared to the internal image quality of the instruments. In the laboratory we were able to use the star simulator together with an auxiliary CCD with smaller pixels and an enlarging optics to measure the point spread function of the FORS instruments.

In November 1996 the first unit of FORS was completely assembled and mounted to the telescope simulator. The first test was the measurement and optimization of the instrumental flexures. This was done with the internal pinhole of the instrument and an external pinhole on top of the telescope simulator, respectively. From the small image motion while tilting and rotating the instrument we had to find an optimum number of support struts to minimize the instrumental flexures. The image motion was specified to be smaller than 0.25 pixels during 1 hour in standard resolution and 0.25 pixels during 2 hours in high resolution mode. This has to be compared with the image scale of $0.2''$/pixel. After optimization the meassurements with the internal pinhole are within the specification. With the external pinhole similar results were achieved. However, the tests showed that the telescope flange will influence the flexure behavior. Therefore, the final optimization of the support struts will have to be checked out at the telescope. More detailed informations about the flexure tests are presented by Nicklas et al. 1998.[3]

The image quality was tested for the instrument alone and for the instrument together with the various optical components such as filters, grisms and polarization optics. The specification of 70% light in one pixel and 90% in 2×2 pixels was clearly fulfilled. The polychromatic (spectroscopic) image quality was measured with the star simulator. The specification to have 70% in 2×2 and 90% in 3×3 pixels was easily reached on-axis. In both modes imaging and spectroscopy the off-axis image quality tests have to be done with the telescope (see below).

Tests of the electro-mechanical components were undertaken simultaneously. Some had already been carried out for the three separated segments of FORS. Since the instrument tests have been started at the telescope simulator the movable components are operated under full software control. During the extensive optical tests and flexure measurements the adjustment of the electronics and the software could be continuously optimized under very realistic working conditions. The instrument software development is still in a very busy phase upgrading the fundamental parts of the instrument control and developing the observer related software. At present we can already start "observation templates" remotely controlled to get calibration exposures. Graphical user interfaces exist to prepare the observations.

The special configuration of the movable slit jaws for multi-object spectroscopy provides an efficient way to study the effects of the mechanical properties and problems of the slit jaws such as dust and internal flexures. The relative movement δD of the slit jaws can be done very accurately under control of the instrument software. In this case one can measure the width of the slitlets D and the deviation from parallelism by the equation $D = \delta D/(I_2/I_1 - 1)$ from the intensity ratio I_2/I_1. With this method we could adjust the encoder zero points and check two slitlets which showed some unexpected deviations from the specified overall slit width. We found it very important to clean the slitlets before mounting the instrument to the telescope to avoid dust. During the operation of the telescope the linear atmospheric dispersion corrector (LADC) will shield the instrument against the dust even when the entrance shutter of the instrument is open. After cleaning and adjusting the slit jaws, all slitlets were clearly within the specification of 10μ.

A systematic analysis for contaminating scattered light and ghost images was undertaken. Sky concentration effects from the curved camera optics will be small ($< 2\%$). The filters in the parallel beam are tilted to avoid ghost images. However, this was not possible for the polarization optics. During the tests in the assembly hall we found that the ghost images will be less then 10^{-5} of the incoming intensity. For polarimetric observations the ghost images are expected to show complex structures from the individual components of the retarder plate mosaics, which are not perfectly parallel. These effects are being studied currently.

6. THE TESTS AT THE TELESCOPE

Although many tests have already been done in the assembly hall, some of the tests have to be repeated during day or night time after reassembling the instrument on Cerro Paranal. After the functional tests and the adjustment of the instrument mechanics, electronics, optics and control software the commissioning phase will start in September

1998 to evaluate the proper function of FORS 1. A comprehensive commissioning plan has been worked out jointly by ESO and the FORS consortium.

Some commissioning tests can be done only together with the telescope: e.g. the image quality over the field of view. This has to be done with "real stars" to avoid the overcorrection we have described above. Measurements of the image motion during long exposures are foreseen at the telescope, too. This will require a properly working telescope and TV-guiding system during the tests.

The polarization optics will be adjusted with a perfectly polarized beam of light from a Glan-Thomson prism. Although this investigations can be done in day time we will observe standard stars thereafter, to have an unbiased small sample of faint standard stars for future observations.

System throughput and photometric transformation coefficients and zero points will be calibrated during the first days at the telescope as well as other quantities like image scales and distortion. All these measurements have to be repeated for the standard Bessell and Thuan-Gunn filters, observing clusters with photometric and astrometric standard stars. Finally the limiting magnitudes for all observing modes will be tested with long term exposures at very good environmental conditions.

7. ACKNOWLEDGMENTS

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