# Commissioning of the FORS instruments at the ESO VLT

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## ABSTRACT

FORS (**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 spectropolarimetry of faint objects. Two almost identical copies of the instrument (FORS1 and 2) were built by a consortium of three astronomical institutes (Landessternwarte Heidelberg and the University Observatories of Göttingen and München) under contract and in cooperation with ESO. FORS1 was installed in September 1998 and FORS2 in October 1999 at the Cassegrain foci of the ESO VLT unit telescopes nos.1 and 2. FORS1 is in regular operation since April 1999. Regular observations with FORS2 are scheduled to begin in April 2000.

There were two commissioning periods foreseen for each of the instruments to test the performance and reliability under various observing conditions. Extensive tests were done on the electro-mechanical functions, image motion due to flexure, optical quality, instrument software, calibration and in particular on the multi-object spectroscopy. Also a detailed characterization of the instrument's properties in the different observing modes has been carried out. In this paper, the procedures of the tests and the results obtained during the commissioning runs are presented in detail and compared with the specifications.

**Keywords:** Instrumentation, Optics, Focal Reducer, Commissioning

## 1. INTRODUCTION

To ensure a proper functioning of the instruments from the beginning of the regular observations, two commissioning periods for each of the instruments were foreseen. The first period was dedicated to instrument tests to verify the proper functioning, to evaluate the basic performance parameters and to optimize the observing procedures of FORS. A performance assessment phase followed to evaluate the data obtained and to correct hardware or software problems encountered during commissioning 1. The second phase was dedicated to perform a complete characterization of the instrument properties, to deliver input for the calibration plan and to test the data flow system. Commissioning 2 ended with the hand-over of the instrument to ESO.

The design of the instrument and the various observing modes are already described in several publications, see e.g. Seifert et al., 1994[1]. Therefore we give here only a short overview: Imaging with two different image scales, low-dispersion spectroscopy with long slits, moveable slitlets and masks (only FORS2), echelle spectroscopy (FORS2) and imaging polarimetry as well as spectro-polarimetry (only FORS1). The wavelength range covers 330 nm to 1100 nm. A view of FORS2 attached to the VLT telescope no.2 is shown in Figure 1.

Both instruments were already extensively tested at our Telescope and Star Simulator (TSS) in Germany before being mounted at the telescope. Critical items like the optical quality, proper functioning of the electro-mechanical functions, instrumental flexure and the software for instrument control and observation support proved to be within the design goals. Moreover some minor problems have been fixed and the handling and maintenance procedures were approved. A detailed description of those tests and the results can be found in Szeifert et al., 1998[2].

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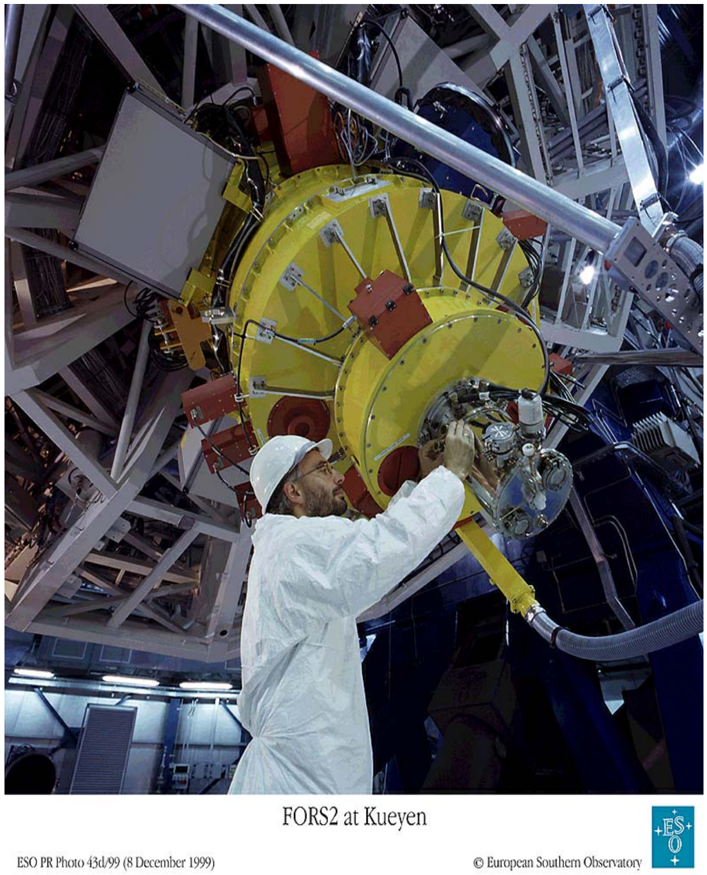


**Figure 1.** FORS2 attached to VLT telescope no.2.

The tests performed during the commissioning periods are described in the following sections. In Section 2 the tests related to the performance of the optics of the instrument are summarized. The tests concerning the stability of the calibration of FORS are described in Section 3, Section 4 is dedicated to software tests performed. The High Time Resolution Mode (HIT) which was implemented in FORS is mentioned in some detail in Section 5.

The results given in the following sections were deduced from data obtained during both commissioning runs for both instruments unless otherwise noted.

## 2. OPTICAL PERFORMANCE

### 2.1. Image Quality

The FWHM of the PSF of the best seeing limited images obtained with FORS in standard resolution (SR, 0.2 arcsec/pixel) and high resolution (HR, 0.1 arcsec/pixel) mode during the commissioning runs are listed in Table 1 for the UBVRI filter bands. As the instrument's intrinsic image quality as calculated and measured on-axis at the TSS is better than 80% of the light within 1 pixel, the values in Table 1 only reflect varying seeing conditions. The measured image quality on the detector was nearly always better than the value delivered by the seeing monitor and identical to the value measured on the guide probe of the telescope.

Plots of the PSF of the instrument in the SR and HR mode are given in Figures 2 and 3. The tail at the bottom in the PSF is caused by the seeing.

| Filter | SR | HR |
|---|---|---|
| U | 0.84 arcsec | 0.48 arcsec |
| B | 0.52 arcsec | 0.44 arcsec |
| V | 0.54 arcsec | 0.36 arcsec |
| R | 0.45 arcsec | 0.54 arcsec |
| I | 0.48 arcsec | 0.39 arcsec |

**Table 1.** FWHM of the PSF of the best seeing limited images obtained with FORS1 and 2.

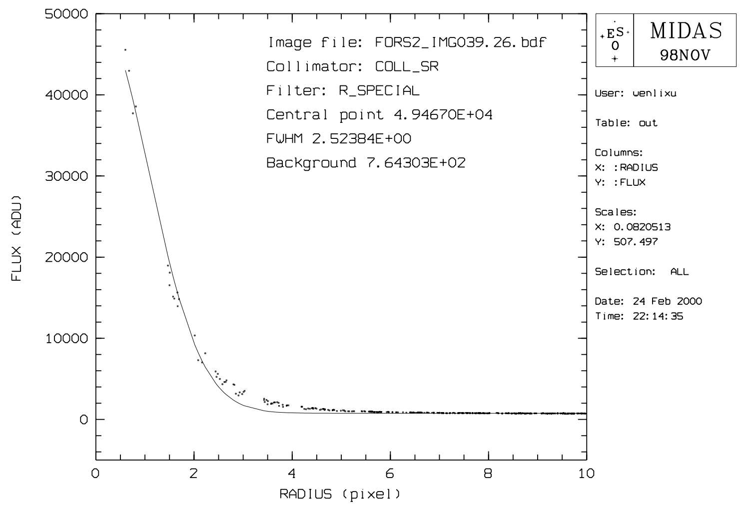


**Figure 2.** PSF plot in SR mode using the R band filter (FORS2).

We note that outside the commissioning runs at times of better seeing smaller FWHM values have been observed. The best images were reported for FORS1 in March 1999 with a FWHM of 0.25 arcsec in I band (see ESO Press Release 06/99 of March 6, 1999).

## 2.2. Spectral Resolution

The spectral resolution was measured on sky. Spectra of the Orion nebula were taken with several grisms both in SR and HR mode using a longslit with 0.3 arcsec slit width. In all cases no deviation from the theoretical resolution could be detected. In the following Table 2 the results are summarized. The FWHM of the spectral lines is given in pixels, which should be, according to the slit width, slightly less than 2 pixels in SR and less than 3 pixels in HR mode. The specification for the spectral resolution is met for all grisms in all modes.

| Grism | SR | HR |
|---|---|---|
| 600B | 1.97 | 2.51 |
| 1028z | 1.77 | 2.58 |
| 200I | 1.93 | 2.62 |
| 300V | 1.90 | 2.85 |

**Table 2.** FWHM of spectral lines measured in SR and HR mode (FORS1 and 2).

## 2.3. Photometric Zero Points

During the commissioning phases fields containing photometric standard stars (Landolt, 1992[3]) were observed regularly in SR and HR mode and all filter bands. From these data the photometric zero points were determined. The zero point of an instrument is the magnitude of a star which produces 1 $e^-$/s. The zeropoints determine the connection between observed counts and a photometric system and on the other hand between counts and astrophysical

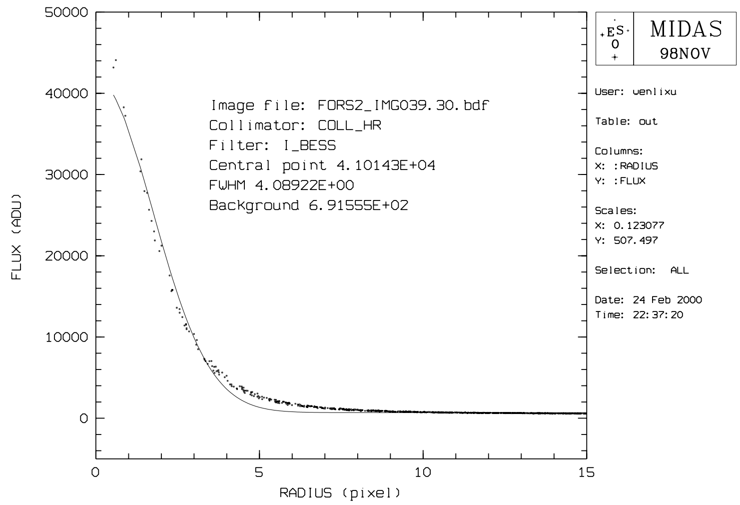


**Figure 3.** PSF plot in HR mode using the I band filter (FORS2).

measurements. This is equivalent to the total efficiency of the system including atmosphere, telescope, instrument and detector.

| Filter | COM 1 | | COM 2 | |
|---|---|---|---|---|
| | ZP SR | ZP HR | ZP SR | ZP HR |
| U | 24.8 | 24.8 | — | — |
| B | 27.5 | 27.4 | 27.4 | 27.4 |
| V | 27.9 | 27.9 | 27.9 | 27.9 |
| R | 28.0 | 28.0 | 28.1 | 28.0 |
| I | 27.0 | 27.1 | 27.1 | 27.1 |

**Table 3.** Photometric zero points for FORS2 in the different filter bands both for SR and HR mode. The U filter was not available for the second period.

The stability of the zero point was investigated in detail since there was a problem with a contamination of the detector surface. After the detector was baked (before commissioning 2), the zero points improved by about 0.1 magnitudes. However due to new contamination during the commissioning 2 period the zero points returned slowly to the previous lower values.

Also the complete set of photometric transfer coefficients as well as the atmospheric extinction at the observatory were determined.

## 2.4. Distortion

The image distortion was measured on astrometric fields in globular clusters. Using the measured positions of the stars in the whole field of view, a third order polynominal was fitted to the data. The accuracy is determined by the accuracy of the astrometric positions. The measurements were done in the V band. The relations to determine the deviation of the position measured on the detector from the real (astrometric) position ($r$) are given below. The measured distortion is in good agreement with the design data (SR 0.30%, HR 1.55% at the corner of the field), both for FORS1 and 2.

$$\begin{array}{ll} \text{SR:} & 2.091{*}10^{-9}{*}r^3 - 1.228{*}10^{-6}{*}r^2 + 3.602{*}10^{-4}{*}r \\ \text{HR:} & 9.515{*}10^{-9}{*}r^3 - 3.605{*}10^{-6}{*}r^2 + 1.001{*}10^{-3}{*}r \end{array}$$

### 2.5. Parasitic Light

All light arising not from the direct optical path, as e.g. stray light, ghosts etc. was investigated in detail to characterize these properties of the instrument. As a faint object imager/spectrograph, FORS is highly sensitive to such effects.

**Ghost images:** As all glass/air surfaces are coated, the brightest ghosts have less than $10^{-5}$ relative intensity. The filters and grism surfaces in the parallel beam are tilted to avoid ghosts. The main sources for ghosts are the polarization optics (not tilted, FORS1) and the 'Longitudinal Atmospheric Dispersion Corrector'(LADC) which is implemented in the telescope. But even those ghost images are in the worst case less than $10^{-3}$. A bright star was located at different positions in the field for this test. Some of the interference filters do actually give rise to ghosts with higher intensity (up to 1%) due to internal reflections. Those filters will be replaced in the near future.

**Direct sky light:** The VLT telescopes are optimized for the Nasmyth focus in the infrared and have no baffles. For Cassegrain instruments, the secondary mirror does not prevent direct sky light for reaching the focal plane. A small retractable ring near the secondary is used to block direct sky light down to the noise level of the measurements done. A bright star was placed at several off-axis distances and the background was measured.

**Stray light:** A bright star in the field was occulted by using one of the slitlets of the MOS unit and the remaining increase of the background near that star was investigated. No significant stray light was found.

**Sky concentration:** Light reflected back from the detector to the optics can cause the so called sky concentration, i.e. the background level in frames is increased near the center. The measurements were done by opening and closing adjacent MOS slitlets and by measuring the light in the shaded areas. The sky concentration was found to be in all filter bands less than 0.7%.

### 2.6. Polarization

FORS1 allows for measurement of linear and circular polarization both in the direct imaging as well as in spectroscopic mode. The accuracy of the polarization measurement is better than $10^{-3}$. Chromatic effects on the retarders are small as we are using superachromatic ones. As an example, the circular and linear spectro-polarimetric measurement made of the white dwarf GD229 are shown in Figures 4 and 5, respectively. The error in the polarization is in both cases less than $10^{-2}$ for this test measurement.

**Instrumental polarization:** Measurements of the linear polarization of an unpolarized star give the result that the instrumental polarization is less than $5 \times 10^{-4}$ in the Stokes parameters Q and U. Thus it can be neglected for most purposes.

**Stokes parameter cross talk for the $\lambda/4$ retarder:** It was shown by measurements with a Glan-Thompson prism that by taking two images with the quarter wave plate rotated by 90 deg the cross talk can be nearly fully eliminated.

## 3. STABILITY AND REPEATABILITY

### 3.1. Instrumental Flexure

Special attention was paid to this point as FORS uses a passive compensation for image motion due to instrumental flexure. While the total flexure is up to 100 microns from flange to detector, the resulting image motion was specified to be less than 6 microns. The image motion was measured using an internal pinhole mask and moving the telescope to various zenith distances and rotator positions. The specification regarding image motion is fulfilled for FORS1 (Nicklas et al., 1998[4]) as well as for FORS2 (Schink et al., 2000[5]). On long exposures in direct imaging as well as spectroscopy, the measured broadening was less than 0.2 pixels for exposures lasting half an hour.

This allows to do all calibrations for science observations during daytime with the telescope in zenith position. No time is needed to do wavelength and/or flatfield calibrations during the night and this allows an efficient use of the observation time.

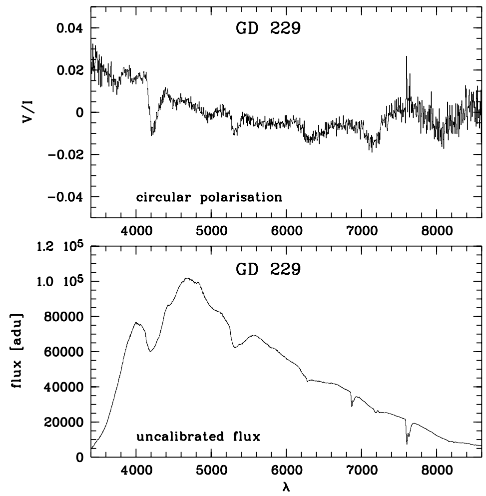


**Figure 4.** Circular polarization of the white dwarf GD229.

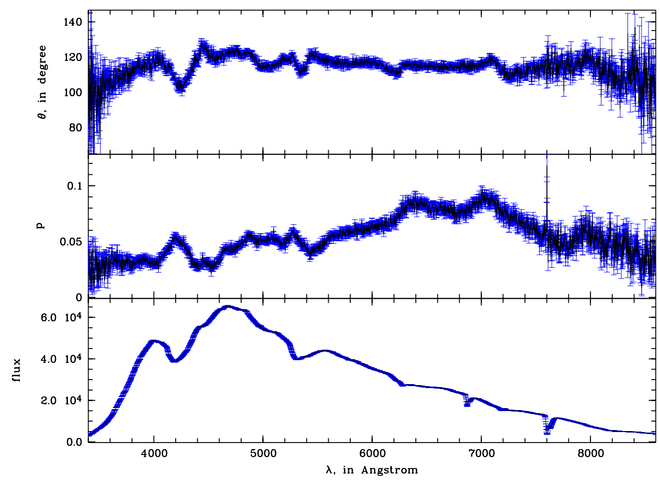


**Figure 5.** Linear polarization of the white dwarf GD229.

### 3.2. Wavelength Calibration

The wavelength stability at different positions of the instrument with respect to the vector of gravity was investigated using an internal pinhole in order to take wavelength calibration spectra. Apart from the instrumental flexure itself, the movements of spectral lines was less than 0.1 pixels for zenith distances up to 60 deg and full rotation of the instrument. Thus the grisms do not show any significant additional flexure within their mountings although they weight up to 5 kg.

### 3.3. Electro-mechanical Functions

The most critical part are the focal plane arrangements for multi object and longslit spectroscopy (see for details Schink et al., 2000[5]). This includes the Multi Object Spectroscopy (MOS) unit, which allows to position 19 slits of 22.5 arcsec slit length each, and the Mask Exchange Unit (MXU) which is available for FORS2. Moreover a mask dedicated for longslit spectroscopy is permanently installed and gives the possibility to choose one of nine predefined slit widths in the range of 0.3 to 2.5 arcsec.

The MXU allows to put a laser cut mask with arbitrary slit width, length, tilt and shape in the focal plane. A magazine of 10 masks makes a flexible use during the observation nights possible. The tests during commissioning were focused on reliability of the complete unit and repeatability of the positioning of the masks. No problems occured during the testing.

The MOS unit is driven by 38 motors (2 for each slitlet). The tests on the MOS included positioning accuracy, slit width accuracy, repeatability, long term movement tests and temperature dependence of the positioning. Most of those tests were done using set-ups for star fields with measuring of the relevant parameters. The specifications for the unit are fulfilled.

## 4. SOFTWARE

For an efficient preparation of multi object spectroscopic observations a special tool was developed: FIMS, the FORS Instrumental Mask Simulator. For a detailed description see Hummel, 2000[6]. The full software chain from observation preparation – through templates executing the sequences of exposures specific for different observing modes – and the observation software which acquires the targets and takes the exposures up to the instrument control software which sets the different instrument functions at the specified positions was tested. In addition the maintenance software necessary for preparation of the instrument for astronomical work was tested under real conditions. In particular the following tests were performed:

- Tests of the software used for preparation of observations
- Tests of the templates for all observing modes
- Tests of the acquisition procedures for spectroscopic modes (target/slit alignment, high accuracy method – 0.04 arcsec, fast alignment – 0.3 arcsec)
- Interface tests to the Telescope Control Software and Archive
- Tests of the control software under real conditions
- Calibration of the function focus = f (temperature)
- Calibration of the function scale = s (temperature)

## 5. HIT

This mode was not originally foreseen but was found to be useful and feasible and has been implemented in FORS2. The maximum time resolution is 1.2 ms, giving the possibility to investigate fast variable phenomena.

Two high-time resolution modes are available with FORS2: in the so-called trailing mode a mask with a slit at the lower end of the field is inserted in the focal plane of the instrument. In this way the whole CCD is covered except the slit in which the object under investigation is positioned. When the shutter is opened, collected charges are shifted upward and the CCD is read out at the same time. In this way, several images (or spectra) of the object are taken at different times. The result is a series of images, showing the variation with time.

For the investigation of periodic phenomena the so-called periodic shifting mode can be applied. In this mode a mask with a slit in the middle of the field is used. When the shutter is opened, collected charges are shifted upwards until the rim of the CCD is reached. Then the shutter is closed and charges are shifted back to the lower end of the CCD. After a synchronisation delay which allows to start at the right phase, the shutter is reopened and the whole sequence starts again. When a predefined number of repetitions is reached the whole CCD is read out. Both high-time resolution modes are described in more detail by Cumani and Mantel, 2000[7].

Both trailing modes were tested on the Crab pulsar with a total exposure time of 2.5 seconds. During this time the images of the pulsar (and some neighbouring stars) were shifted up the 2048 rows of the CCD. Every individual exposure therefore lasted 1.2 milliseconds which was the time resolution achieved in this test. Figure 6 shows an individual CCD frame obtained in that way. The bright continuous line is produced by a normal, non-variable star, and above it the series of dots representing the individual pulses of the Crab pulsar, following each other in intervals of 33 milliseconds. It is also clearly visible that the dots are alternatingly brighter and fainter: the double peaked profile of the pulses. The full period is from one high peak to the next, and the picture shows therefore 6 consecutive revolutions of the neutron star. Time runs from left to right, one pixel in x is 1.2ms, giving a total time of 2.46 s all over the detector.

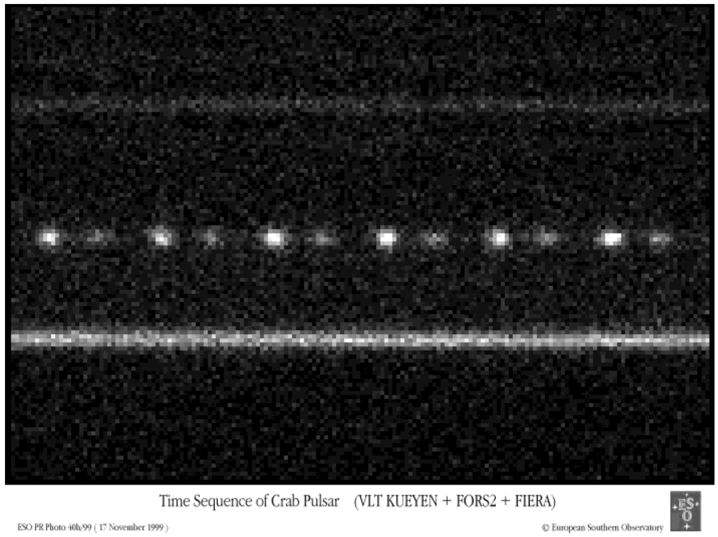


**Figure 6.** CCD frame of a high-time resolution light curve of the Crab pulsar in white light. Time runs from left to right, one pixel in x is 1.2ms. The lower bright continuous line is produced by a normal, non-variable star.

## ACKNOWLEDGMENTS

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