The new FORS Pipeline

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ABSTRACT

Over the last decade of successful science operations with the VLT at Paranal, the instrument pipelines have played a critical role in ensuring the quality control of the instruments. During the last few years, instrument pipelines have gradually evolved into a tool suite capable of providing science grade data products for all major modes available for each instrument. In this paper we present the major enhancements that have been recently brought into the body of the FORS pipeline. The algorithms applied for wavelength and photometric calibrations have been deeply revised and improved by implementing innovative ideas, and the FORS instrument is now almost fully supported in all of its modes: spectroscopy, imaging and spectro-polarimetry. Furthermore, the satisfactory results obtained with the FORS pipeline have prompted synergies with other instrument pipelines. EFOSC2 at the NTT of the La Silla Observatory already shares with the FORS pipeline the imaging and spectroscopic data reduction code, and the spectroscopic part of the VIMOS pipeline is being reengineered along the same lines.

Keywords: FORS, pipeline, VLT, ESO, data reduction, photometry, multi-object spectroscopy, MOS, polarimetry, spectro-polarimetry

1. INTRODUCTION

FORS[1] stands for the visual and near UV **FO**cal **R**educer and low dispersion **S**pectrograph at the VLT. It is a multi-mode (imaging, polarimetry, long slit and multi-object spectroscopy) optical instrument placed at the UT1 Cassegrain focus of the VLT. It was developed by the Landessternwarte Heidelberg, the University Observatory of Göttingen, and the University Observatory of Munich. Two twin FORS instruments have been in operations for more than a decade (FORS1 was decommisioned in 2009).

Experience over these years has shown that the original data reduction pipeline was conceptually inadequate for yielding science-grade data products. Systematic errors in the wavelength calibration exceeded one pixel, and the spatial distortions were ignored. The algorithm and physical model applied were not compatible with the high resolution grisms, which could not be supported. The flat-fielding correction introduced spurious signals in the scientific products. Photometric solutions were not as accurate as they could be. And finally, the spectro-polarimetry instrument mode remained unassisted.

The effort of rewriting the FORS pipeline anew was estimated to be less than the one required for fixing, maintaining and further developing the old one. Moreover, the old pipeline was among the few ones still based on MIDAS.[2] It needed therefore to be adapted to the new Common Pipeline Library (CPL)[3] as all the other instrument pipelines, in order to reduce the maintenance costs of the observatory data reduction software.

Many efforts have converged to guarantee the quality of the new pipeline: the FORS Absolute Photometry Project,[4] whose purpose was to reach an absolute photometric accuracy of 3 percent in the R band, provided the new strategy for improving the photometric solution. The wavelength calibration and star identification

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procedures have been completely rethought and are now based on the pattern matching[5] paradigm. This is based on reducing to a minimum the required preliminary knowledge of the instrument characteristics, leading to a more robust and general algorithm.

The new pipeline consists of very few (4 imaging, 2 spectroscopic, 2 spectro-polarimetric) recipes and its high quality results have been satisfactorily compared with other independent and even interactive data reduction procedures. The correctness of the error propagation has been confirmed by Montecarlo simulations.

With the new pipeline, a typical observation run can be processed in minutes.

This paper discusses in detail the major enhancements of the pipeline in its different modes, highlighting its reliability and describing only briefly the techniques applied by its different components. The pipeline user manual[6] presents them more exhaustively.

2. IMAGING

The body of the imaging part of the pipeline consists of a set of standard reduction steps (bias substraction, flat-fielding) followed by a source detection and characterization step which is based on SExtractor.[7] The user interface of the scientific recipes allows to fully exploit the possibilities offered by the underlying SExtractor, providing the means to pass on the most significant parameters or to specify a complete configuration SExtractor file.

Imaging data reduction is characterized by a pedantic propagation of photonic noise and CCD readout noise to all of its products. In particular, an error map is associated to each image product.

Pattern-matching[5] is also used for safely identifying the reference standard stars for the photometric solution, independently of the accuracy of the astrometry originally associated to the exposures.

The complete photometric solution is based on the catalogs produced when computing the zeropoints of different exposures, and is obtained by optimal least square fitting of photometric equations which include atmospheric and instrumental effects, such as the filter correction, the instrument zeropoint and the atmospheric extinction for each observed star. Optionally, a correction map relative to the flat-field frame used in the processing of the original scientific frames is produced, and to this purpose also field stars can contribute to the fit. This step is bringing the accuracy of the solution to the 3% level. This method is described in detail in Freudling et al. (2006).[4] The pipeline offers the possibility of freezing any of the parameters fitting the photometric solution, including the magnitudes of individual stars.

The corresponding error propagation does not take the diagonality of the covariance matrix for granted, i.e., the estimates are optimally weighted not just by the inverse of their variances. The derived errors appear nonetheless to be too small. This anomaly has been verified independently, and it can only be attributed to underestimated errors on input quantities.

The atmospheric extinction used for instrument health monitoring is an optimally weighted average of estimates obtained from each observed photometric standard star, assuming a constant instrument zeropoint. This atmospheric extinction is estimated in single exposures and daily monitored for quality control purposes. See Fig. 1 for a trend plot.

3. SPECTROSCOPY

The spectroscopic part of the pipeline consists of only two recipes, one for the calibration frames (arc, flat and bias frames) and another one for the scientific data reduction. Both recipes are equally applicable to Long Slit Spectroscopy (LSS) and Multi-Object Spectroscopy (MOS/MXU) data.

Pattern-matching[5] is applied to the identification of the reference arc lines, which is critical for improving the robustness of this crucial task. The fitted dispersion solution is polynomial and its accuracy reaches 1/20 of a pixel. See Fig. 2 for a Montecarlo simulation of the model accuracy. The spatial curvature is also modelled with a low degree polynomial fitting, whose accuracy reaches 1/100 of a pixel. See Fig. 3 for a typical tracing solution.

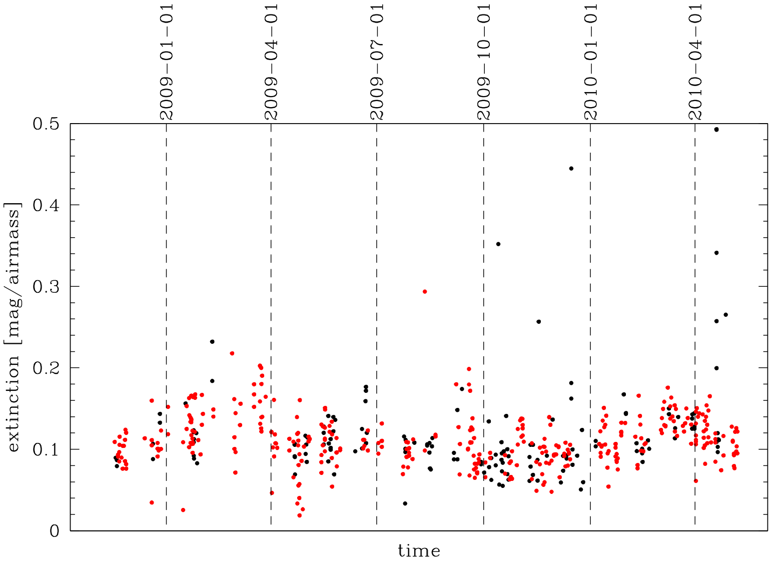

Figure 1. This is the recorded trend of the atmospheric extinction for CHIP #2, filter R. The red dots represent photometric nights, the black ones, non-photometric nights. The decision whether a night is photometric is based on independent checks. On June 18, 2009, a bug was fixed in the pipeline and scatter on measurements is visibly reduced since. The atmospheric extinction in this plot is estimated by assuming a constant instrument zeropoint.

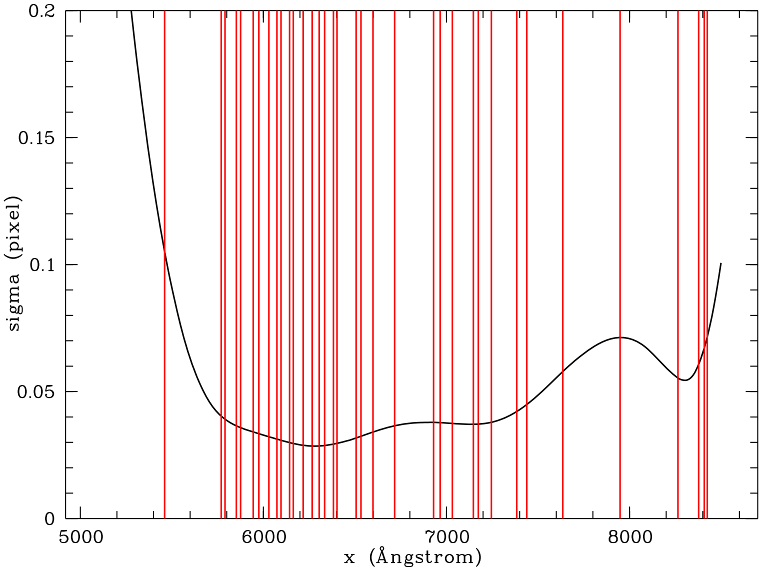

Figure 2. Montecarlo simulation of wavelength calibration model accuracy (from FORS2/MXU 600RI calibration lamp). The curve describes the changing accuracy (in pixel), given at 1-σ confidence level. The vertical lines indicate the positions of the used reference arc lamp lines. It is possible to see that, as expected, the calibration is more accurate where the density of lines is higher. The accuracy of the model degrades rapidly at the blue and red ends of the spectrum, where uncertainties due to overfitting and extrapolation are greater.

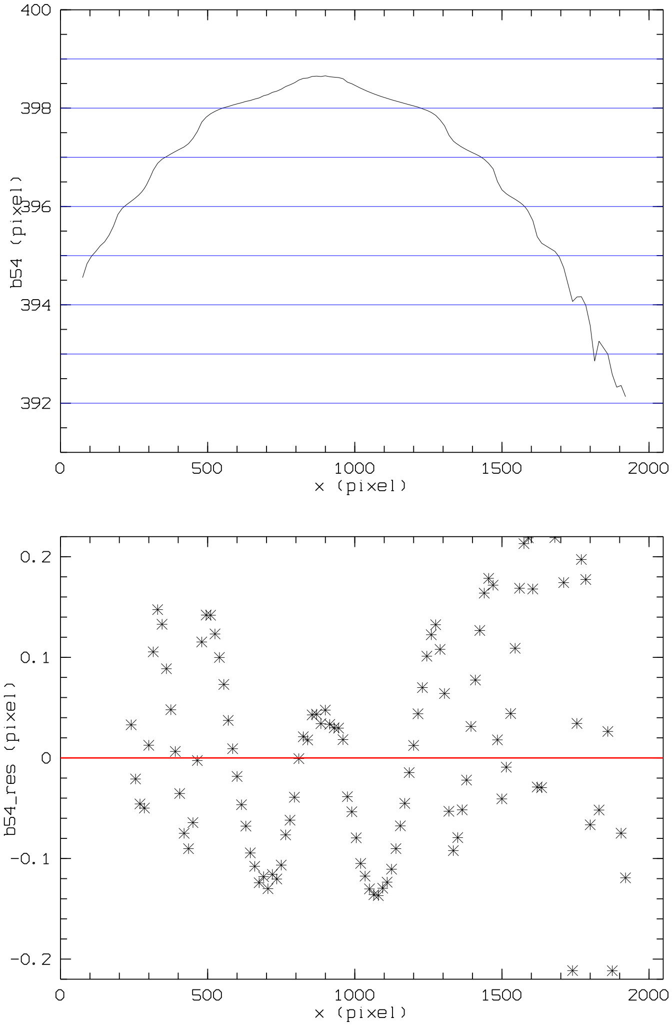

Figure 3. The undulating shape of the trace (image above) and therefore the systematic residuals (image below) are due to the changing pixelization of the spectral edges on the CCD. This not being an optical effect, it is purposefully excluded from the fit.

The calibration recipe also computes a global distortion model which enables the recovery of confused spectral features (edges, arc lines, etcetera). Among the several side products, the recipes provide wavelength and spatial maps of the CCD (both a wavelength and a position within the slit is assigned to each pixel).

When reducing scientific spectroscopic data, the distortion model, which is based on daytime calibrations taken with the telescope at zenith position, can be optionally aligned to the reference sky lines with a typical accuracy of 1/10 of a pixel. The sky can be subtracted either before or after remapping the spectra to constant wavelength and spatial steps. In the former case, a supersampled sky spectrum is built, local to each slit or global to the whole CDD. In the latter one, a median sky is used. Sky subtraction before remapping is typically preferred because it greatly reduces small-scale interpolation problems. The option of subtracting a global sky spectrum is generally unsatisfactory, because the spectral resolution may vary significantly with the position on the CCD. Nevertheless, in cases where a local or a median sky subtraction could destroy spectra from extended objects (i.e., filling most or all of the slit), global sky subtraction is the only possible solution. Optionally, cosmic ray events can be eliminated from the products.

Objects are detected and extracted, either with a simple aperture extraction or with the Horne optimal extraction.[8] A contamination radius can also be defined to minimize the reciprocal contamination of objects in the same slit.

Spectral response and efficiency curves can be determined from spectro-photometric standard star observations. The spectral response can then be applied to the extracted spectra, converting them to physical units at airmass zero.

4. SPECTRO-POLARIMETRY

FORS1 used to be, and FORS2 is, the biggest polarimeter in the world. As of 2007, 72 % of the scientific papers based on ESO polarimetric data referred to observations with FORS1.[9] Although the polarimetric modes are not the most used ones (see Table 1), the predominance of FORS in polarimetric observations further motivated the pipeline support, beyond the necessity for quality monitoring.

Table 1. Percentages of exposure times for the various FORS1 modes over its whole lifetime

Imaging	27.5 %
Imaging Polarimetry	5.2 %
Long-Slit Spectroscopy	25.9 %
Multi-Object Spectroscopy	29.5 %
Spectro-Polarimetry	11.9 %

Since April 1, 2009, the FORS pipeline supports the reduction of spectro-polarimetry data. It is backward compatible, having been successfully tested also with all past instrument settings. The development of the corresponding calibration and science recipes is based on Bagnulo et al. (2009).[10] Imaging polarimetry is currently not supported and, being by far less used that the spectro-polarimetry mode, its implementation is currently a rather low priority task.

The pipeline offers two recipes, one for calibrations and another one for scientific reduction. Both are equally applicable to linear and circular polarization data, and to observations with many slits and objects.

The two polarimetric recipes share most of the functionality with the spectroscopic ones. The added functionality mainly consists of a safe bookkeeping of all the spectra detected and extracted in the different light beams and angles of the polarizer. The extracted spectra belonging to the same source are matched and combined to derive the Stokes parameters as a function of wavelength, together with extended ancillary information. In the reduction of FORS polarimetric data, both ordinary and extraordinary beams are calibrated independently one of another; they are treated as two independent entities. It is only after their calibration that they are combined.

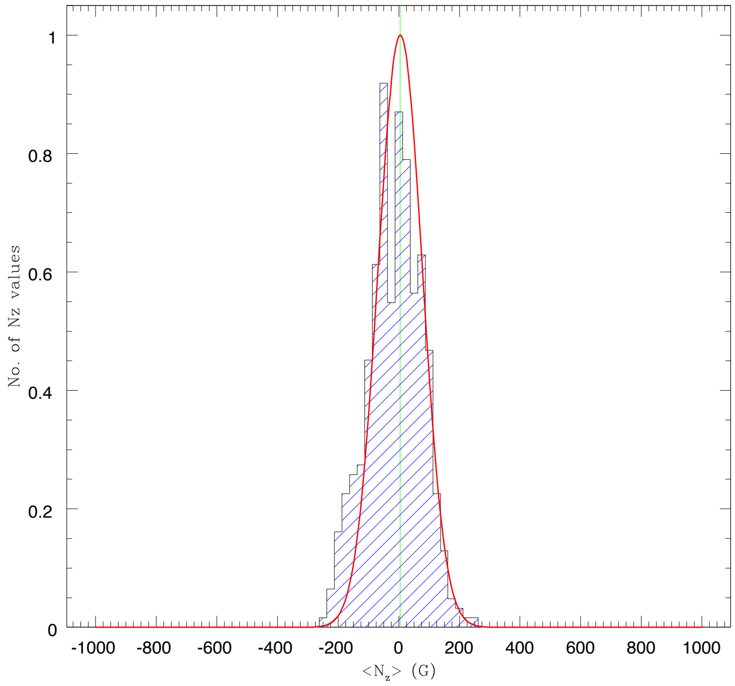

Figure 4. The magnetic field measured on spectral lines profiles compared with the null parameters[10] (expected value zero) scatters in agreement with the error propagation computed by the pipeline. The histogram is based on 1000 Montecarlo simulations of input raw polarimetric frames (both calibration and scientific exposures). The method applied for the estimation of the magnetic field is described in Bagnulo et al. (2002).[12]

The total spectrum of each source is also reconstructed out of its components. A chromatism correction can be applied in the case of linear polarization observations. Finally, the observed polarization of reference standard stars is compared with the expected values.[11]

The standard error propagation is also applied, and this is consistent with the observed variance of the null Stokes parameters. See also Fig. 4 for a visual check of the validity of the error propagation.

5. SPIN-OFFS OF THE NEW FORS PIPELINE

The principles on which the new pipeline relies make it very easy to adapt it to any MOS instrument. In its testing phase and before being put into operations, the pipeline was fed with data from other ESO spectrographs (VIMOS, EFOSC2 and EMMI) and from the Hobby-Eberly Telescope Low Resolution Spectrograph.[13] All data could be reduced satisfactorily.

There are now two spin-offs of this project at ESO, the EFOSC2 pipeline and the VIMOS pipeline. Despite a few operational and instrumental differences, they use exactly the same code, yielding equally accurate, science-grade data products. The new EFOSC2 pipeline is operational since 2009 and the new VIMOS pipeline will be made operational after the detector upgrade planned for the summer in 2010.

In the case of EFOSC2, the imaging and spectroscopic recipes have all been inherited, while the spectro-polarimetry part was not, because of the recent move of the instrument from the 3.6m ESO telescope to the NTT telescope, where it is not mounted on the Cassegrain focus. Being at a Nasmyth focus, the inclined folding mirror in the beam introduces instrumental polarization which needs to be modelled. After that, EFOSC2 will take advantage of the polarimetric recipes straightforwardly, too.

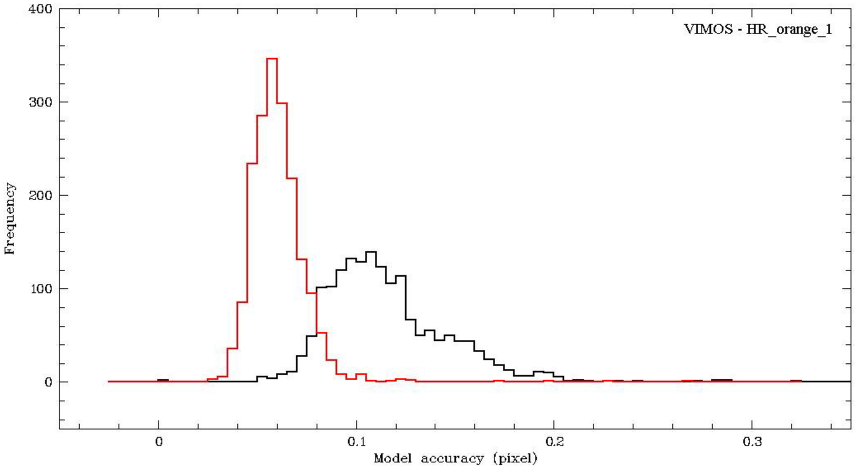

Figure 5. Comparison of the wavelength solution accuracy between the old VIMOS pipeline (black) and the new one (red), on VIMOS data taken with the HR_orange grism. The histograms represent the distribution of the model residuals of 1700 solutions. The uncertainties of the new pipeline are centered around a lower value and are nearly gaussian, displaying a failure rate less than 0.1%.

In the case of VIMOS, the spectroscopic recipes have been inherited to replace the corresponding part of the original pipeline, which had long standing problems similar to those the old FORS pipeline had: among others, a significant lack of accuracy in the wavelength solution (see Fig. 5) and the fact of not being based on the CPL.

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