The FLAMES-UVES Pipeline

In this paper we describe features associated with the data reduction of UVES when operated in Fibre Mode, the required calibrations, the data processing steps and the quality checks performed by the pipeline. We also summarise some results.

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FLAMES, the Fibre Large Array Multi-Element Spectrograph, is the multi-object, intermediate and high resolution spectrograph mounted at the Nasmyth A platform of UT2 of the Very Large Telescope (VLT, see Pasquini et al. 2003, or www.eso.org/instruments/flames). Among its components is the link to the UVES Red Arm fed by eight fibres with a nominal resolution power of R=47,000. The UVES red arm also has a fibre link, the *SimCal* fibre, to a calibration unit.

To solve the specific problems associated with the FLAMES-UVES data reduction, a new data reduction software (DRS) has been developed in a collaborative effort between ESO and the Ital-FLAMES consortium. The software is offered to the user community (www.eso.org/projects/dfs/dfs-shared/web/vlt/vlt-instrument-pipelines.html) as part of a MIDAS context and extends the UVES pipeline functionalities (Ballester et al. 2000).

Pipelines are crucial in supporting operations of the VLT instruments. They are used mainly in three modes: 1) Paranal Science Operations (PSO) uses them as a quick-look and quality control tool to monitor the instrument status almost in real-time and to detect if a calibration or an observation needs to be repeated. PSO monitors the Quality Control (QC) parameters which are logged by the online environment. 2) The Data Flow Operation's department (DFO) in Garching provides permanent and in-depth knowledge of the instrument status. QC parameters are extracted from the data, stored in a database and made available via the Web (www.eso.org/qc) to PSO and the user community. From this information it is possible to control, predict, and often improve the performance of the instruments (QC articles can be found under www.eso.org/qc). Additionally, DFO creates calibration products to reduce Service Mode science observations. 3) Users may use a pipeline to interactively reduce data at their home institutes. To achieve such demanding goals, a pipeline must be robust, reliable and able to work in an unattended, fast and flexible way.

Required calibrations

Several calibrations are necessary to reduce FLAMES-UVES science data. Some of them are common to UVES data obtained in Slit Mode such as biases, necessary to evaluate the read-out of the detector at zero integration time, as well as darks to estimate the detector read-out arising from the isotropic thermal background emission from the instrument.

As the UVES instrument setup may have a drift of up to a few pixels, a set of Slit Flat Fields in echelle mode is taken to correct PSFs for varying pixel-to-pixel efficiency. To be able to evaluate inter-order background and to cover the entire fibre Y span, three sets of three slit Flat Fields each, taken at three different Y positions, are used.

Other calibrations are specific to the fibre mode. A format check frame is obtained by illuminating the *SimCal* fibre with a ThAr lamp. A single fibre flat field is taken by exposing the *SimCal* fibre with a continuum source. These two frames are used to bootstrap the wavelength calibration and the order and fibre trace definition, respectively.

A frame obtained while illuminating all the fibres with a ThAr lamp is taken to find a wavelength calibration solution and a frame taken when illuminating all fibres with a continuum source (all-flat) is needed to compute different fibre throughputs.

A set composed of two exposures illuminating odd-numbered (odd-flat) and even-numbered (even-flat) fibres respectively is also taken to have a set of uncontaminated fibre flat fields for accurate cross dispersion Point Spread Functions (PSFs) evaluation. These are used to assess and correct the non-negligible contamination of adjacent fibres during the extraction of each fibre spectrum.

The user may request all-flat frames at night to get very accurate flat-field corrected science frames. These are obtained by illuminating the fibres with the light reflected by a Nasmyth screen. If particularly accurate wavelength calibrations are required, observations are done in *SimCal* mode, with seven fibres allocated to objects and sky and the SimCal fibre fed by a ThAr lamp.

Data reduction steps

For the FLAMES-UVES data reduction (Mulas et. al. 2002.) the following steps are required:

1. A master bias and a master dark are created and subtracted from the other raw frames.

2. The location of the *SimCal* fibre and a selected list of ThAr lines are determined with the help of a physical model of the instrument on the format check frame. A guess-line table and a guess-order table are generated.

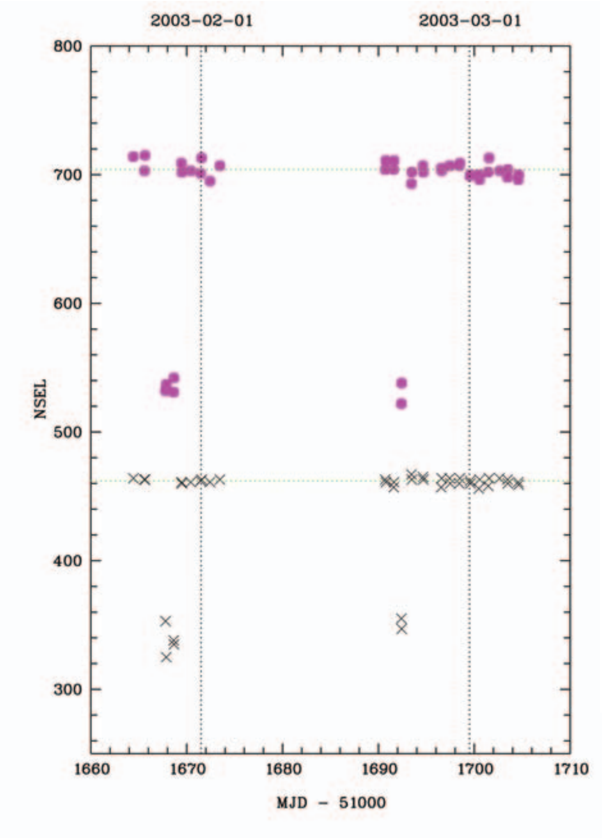
3. Using the single fibre flat field frame a more precise guess-order table is created. Such a table is used to bootstrap the fibre-order tracing and the frame itself to extract the ThAr spectra carried from the *SimCal* fibre in science observations taken in *SimCal*-Mode.

4. From each set of slit Flat Fields a Master Slit Flat field is derived to lower the noise level.

5. The order-fibre definition is made on the odd and even fibre flat field spectra and is refined on the all fibre flat field spectra starting from the guess-order table determined previously. This generates a raw order-fibre table which will be refined to correct for fibre shifts.

6. The slit flat fields positions and extensions are measured in order to define the minimal set which fully covers the maximum Y span. The slit flat field frames are then equalised in flux and cleaned.

7. As the extraction is very sensitive to



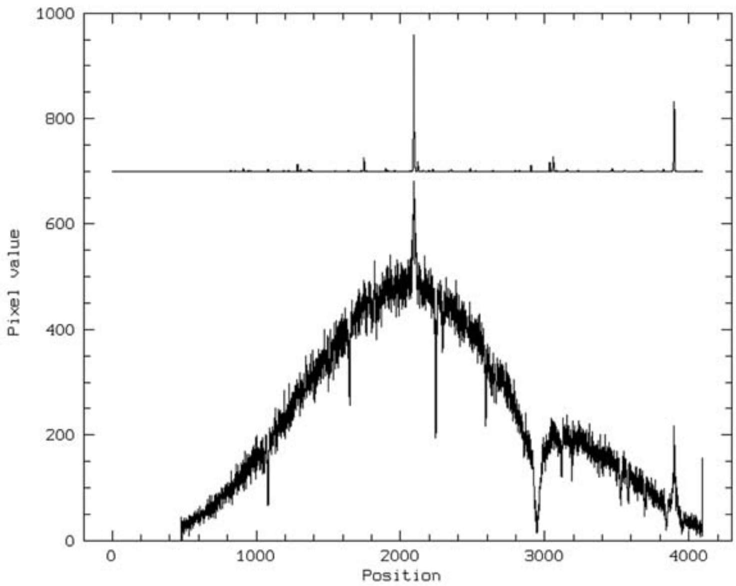


Figure 1: (Left:) Trending of the number of selected lines in format check frames with 580 nm central wavelength recorded during the science verification phase and the first FLAMES Service Mode period. Results for the lower CCD are plotted as filled circles, for the upper CCD as crosses. The green horizontal lines indicate reference values. (Right:) The lower part of the plot shows H_β observed on the fibre next to the one fed by a ThAr lamp (rescaled by a factor 1000, shifted, at the top). The spectral contamination coming from the adjacent fibre is of the order of 0.001.

mismatches in the assumed fibre positions, fibre shifts are determined and corrected during data reduction.

8. Odd and even Flat Fields are background subtracted, divided by the slit Flat Fields to get their PSFs and normalised to simplify fibre shifting.

9. The all-fibre Flat Field is (standard or optimally) extracted, the resulting spectra are stored as relative normalisation factors for the subsequent reduced science spectra so that the fibre positions and transmittances in science frames can be measured later on.

10. During wavelength calibration each fibre ThAr spectrum is extracted and ThAr lines are detected above the background. They are then located and identified using a previous guess-solution and a line table is generated containing independent solutions for all fibres.

11. The science frame is extracted. A correlation function between the science frame and a synthetic frame composed of Gaussian shaped fibres is computed as a function of the cross dispersion shifts of the simulated fibres. Its maximum yields to the measured shift of the fibres on the science frame with respect to their positions on the all fibre flat field frame.

12. The single fibre PSFs are shifted accordingly, and re-multiplied by the slitFF frames. In this way one mimics calibrations taken simultaneously with the science frame. Standard or optimal extraction is performed.

13. Using standard extraction, the adjacent fibres' contribution to the flux centred over one fibre is obtained using an integration over the same interval of the fibre PSFs. The solution of the resulting linear system gives the disentangled spectra.

14. Using optimal extraction the whole fibre pattern is fitted by a linear combination of all fibre PSFs. The solution of the resulting linear system gives the disentangled spectra. Next, a kappa-sigma clipping is performed to identify and reject bad-pixels. Thus, the system solution has to be iterated until convergence is achieved. Optimal extraction provides a computationally more expensive but more accurate solution than standard extraction.

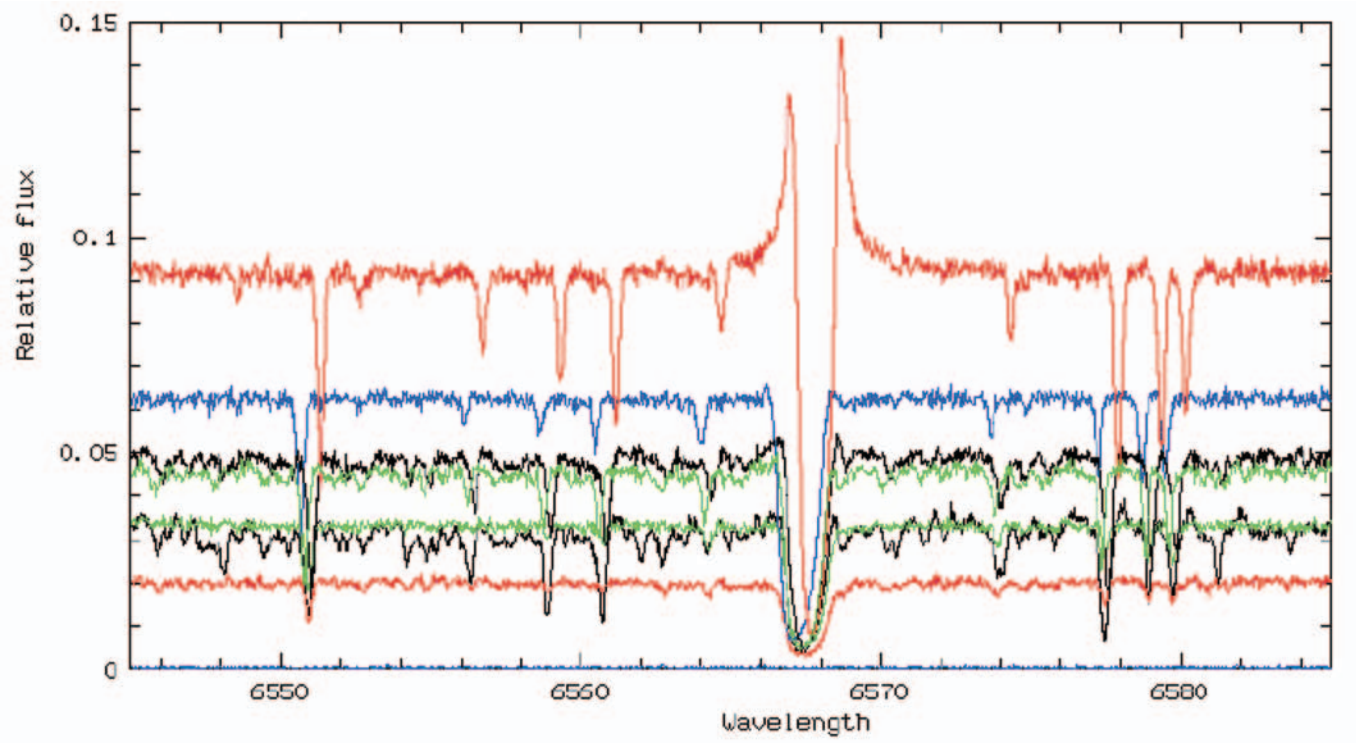
The results of the extraction are the deconvolved spectra in pixel-order space (both raw and throughput normalised) along with their variances and bad pixel masks. The right panel of Figure 1 shows that the residual contamination from adjacent fibres is only of ≈0.001 after data reduction. Finally, the extracted spectra are wavelength calibrated and merged.

Quality Checks

One of the main tasks for a pipeline is to produce Quality Control (QC) parameters, which are logged both in the FITS header of the pipeline products and by the online environment in ASCII files. The FLAMES-UVES pipeline generates QC parameters for each reduction step (see Wolff et al. 2004).

During master bias generation the read-out-noise of the master and of one raw frame are measured to verify the overall CCD stability. The pipeline also determines the average value of the master and any residual slope along X and Y to spot potential global and local problems on the CCD. During master slit flat field generation the number of frames co-added is recorded.

The spectral format instrument stability is monitored on format check frames. Using a reference format check frame and cross-correlating the guess-table solutions obtained on the actual and reference frame, it is possible to measure shifts of the spectral format. As an example, left panel of Fig. 1 shows the number of selected lines in format check frames during science verification and the first FLAMES Service Mode period. On two occasions, there have been shifts of the spectral format in cross-dispersion direction of up to ten pixels. Such shifts made a proper data reduction using daytime calibration impossible. But they could be detected easily using format check results because the number of selected lines decreased dramatically. During the single-fibre order tracing step the pipeline checks that the single fibre



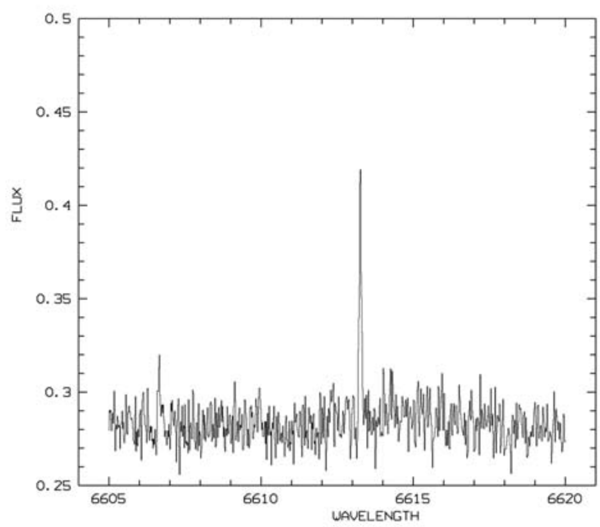


Figure 2: The upper plot shows the reduced spectra of seven giants in ω Cen taken in March 2003 with the UVES fibre around the Hα line. The plot on the left shows the Diffuse Interstellar Band spectrum which appears to be shifted with respect to the "nominal" position.

input frames are well and uniformly illuminated. The order-fibre traces detection step checks that all fibres are traced for each detected order. This is necessary to generate proper wavelength calibration solutions to calibrate the extracted science data. It measures cross order shifts between the all fibre flat field and the odd and even fibre flat fields.

The wavelength calibration step measures the spectral power and the residual difference between the line wavelength values from a reference table and the corresponding values obtained from each fibre solution. Good residuals are characterised by an RMS around 0.0004 nm. Typical values of the resolving power are around 48,000. The intensity of a list of ThAr lines is measured in order to monitor the ThAr lamp health. Science data reduction monitors the Y shifts between the science frame and the odd-even frames.

Results

We give here only a few examples of results obtained reducing FLAMES-UVES data. In the top panel of Fig. 2 we show an example of the merged spectra obtained for seven giants of the ω Cen globular cluster.

The bottom plot in Fig. 2 shows the Diffuse Interstellar Band (DIB) known to be present at about 661.4 nm. The shown spectrum was taken toward ω Cen during the FLAMES GTO run by the INAF - Cagliari Astronomical Observatory FLAMES team. The DIB is shifted with respect to the "nominal" position, although not according to the ω Cen radial velocity.

In conclusion, the FLAMES-UVES pipeline has been demonstrated to be a very useful tool to reduce FLAMES-UVES calibrations and science observations since first commissioning, during Science Verifications (Primas, 2003) and then to support operations for more than 20 months. Additionally, although this is just an "extra", FLAMES-UVES pipeline reduced data may be used by users to do science.

Acknowledgements

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