Towards an Automatic Reduction of FORS2-MXU Spectroscopy

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A brief report is presented of a feasibility study for an automatic, science quality spectral extraction of FORS2-MXU spectra using the aXe package developed for slitless spectroscopy. We briefly describe the aXe data reduction concept, which is usually applied to HST-ACS data, and demonstrate the applicability of this concept by reducing a subset of the Great Observatories Origins Survey (GOODS) FORS2 spectroscopic survey.

The large numbers of objects which can be observed simultaneously with modern multi-object spectrographs demand the availability of automatic reduction software. Such pipeline-supported data-reduction is often used in space astronomy. One example is the purpose-built software aXe (*http://www.stecf.org/software/aXe*), which provides science-quality spectra for the slitless modes of the ACS instrument aboard HST. ACS shows a high degree of stability, which allows the production of a generic calibration (e.g., reference files for the trace, the wavelength solution, flat-field and sensitivity curves) for each of the dispersive elements, removing the need to calibrate each individual set of observations. The data-reduction software is then only driven by the object coordinates within the Field of View (FoV). For long exposures, the spectra of thousands of objects can be extracted, which is clearly beyond manual effort. The software has been successfully used on ACS data in various projects such as the Hubble Ultra Deep Field HRC Parallels (Walsh, Kümmel & Larsen, 2004), high redhift supernovae search (Riess et al. 2004) and the Grism ACS Program for Extragalactic Science (GRAPES, Pirzkal et al. 2004). It was designed such that the instrument specific parameters are stored in external configuration files. The configuration files are defined in a very general and thus flexible way. Therefore the software can be easily adapted to new instruments, even multi-slit spectrographs such as FORS2 at the VLT. Currently there is no software reduction package available for the FORS2-MXU mode, which prompted us to conduct a feasibility study of automatic spectral extraction with the aXe software.

The aXe concept

In slitless spectroscopy there are no apertures such as slitlets, which allow only a small region of the sky to enter the spectrograph. An unambiguous conversion between pixel coordinates and wavelength is therefore impossible. All spectral object extractions must be based on local solutions to the trace description and dispersion solution, which are globally described in the configuration file. To evaluate the local solutions, an object coordinate (stored in the Input Object List) must be provided for every object whose spectrum will be extracted with aXe. Taking into account the optical distortions of the instrument, the object coordinates are transformed to the so-called reference position in CCD coordinates, which drives the local solution. In addition to the object coordinates, the Input Object List also contains other parameters such as the object extension. With this information it is possible to adjust the spectral extraction width for each object individually.

Given a stable instrument configuration and operation, the aXe approach of a global calibration makes it possible to extract multi-object spectroscopy data in an extremely efficient and largely unsupervised way. The main task of the data-reduction is reduced to the creation of the Input Object List. Especially for the production of large science-ready data-products, to be stored in Virtual Observatory compliant archives, a software package like aXe is of paramount importance. In the traditional data reduction, the accuracy of the instrumental calibration is limited to the accuracy of the set of calibrations taken with the science data. In the aXe approach of a global calibration, however, the accuracy is limited by the stability of the instrument and the accuracy of the calibration data to calibrate the telescope/instrument setup.

Observing with FORS2-MXU

FORS is the visual and near-UV FOcal-Reducer and low-dispersion Spectrograph for the Very Large Telescope (VLT). FORS2 offers the possibility to insert in the focal plane a mask in which slits of different length, width and shape can be cut with a dedicated laser-cutting machine (MXU mode). The FORS Instrumental Mask Simulator (FIMS) tool is used to design and define the masks. Within the FIMS tool the slit positions and a number of reference stars are selected. These reference stars will be automatically identified on the acquisition image taken within the target acquisition sequence. From these positions the translation and rotation offsets are calculated and transferred automatically to the telescope. Thus one ensures that the objects are accurately located within the slits of the mask. The FIMS tool is very versatile and thus allows designing masks in different ways. The masks are normally based on pre-imaging with the FORS instrument and slits are placed on objects visible on these images. This can be done by hand or in a semi-automatic fashion. One can also create masks on the basis of catalogues only. Common to all of these methods is that the object position is generally not in the centre (along the spatial direction) of the slit. Although the slit positions and dimensions of each mask are carried through to the final science images, the object positions within these slits are not generally stored. Therefore, only the person who has created the mask may have this information. From the viewpoint of automatic data-reduction or the use of this data by other astronomers than the original science team, the absence of the object positions is a major drawback.

Calibrating FORS2-MXU

As a test bed for our feasibility study we have selected the GOODS/FORS2 spectroscopic survey. This data set was chosen since it provides a rich and challenging use of the FORS2-MXU mode. Additionally, we can compare with an existing ”by-hand” data reduction (Vanzella et al. 2005) and thus are able to evaluate the quality of our data products. In Figure 1 a typical mask design and the associated spectral exposure are shown. In our feasibility study we derive a calibration for FORS2 only for the spectral mode of the GOODS data set.

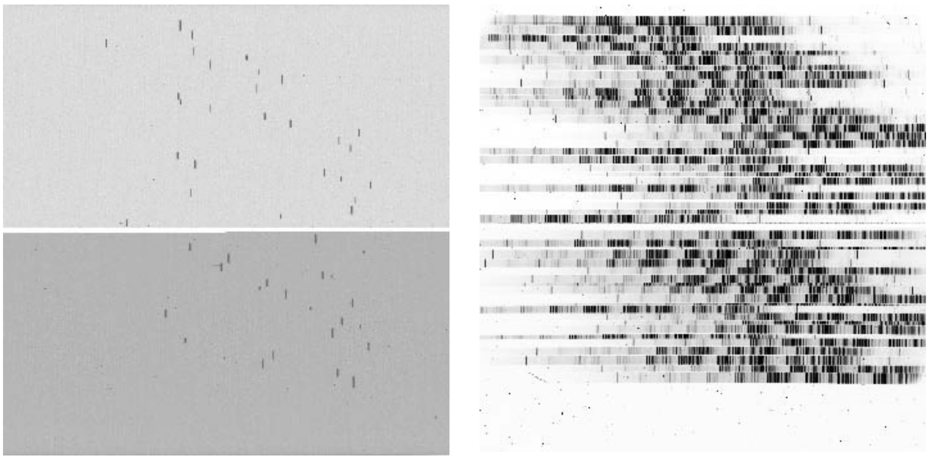


Figure 1: Left: A "through-slit" image of a typical mask from the GOODS/FORS2 survey. The slits appear as short black lines in this image. **Right:** One 20-min spectroscopic exposure showing the spectra obtained with the mask at left and the 300I grism inserted. The typical wavelength range is 600 to 1000 nm at a resolution of R = 660 and thus the signal is dominated by the sky background, which is clearly visible.

In order to apply the aXe software concept to FORS2-MXU data, two major items need to be addressed: (a) the production of the Input Object List which drives the data-reduction tasks; and (b) the construction of the aXe configuration files which describe the imprint of the spectrograph on the incoming beam and other instrument characteristics such as the detector flat field.

In the case of FORS2 one can establish the overall sky-coordinate to CCD-coordinate transformation via the mandatory through-slit images and the known optical distortions of the instrument. In the absence of individual object coordinates one can instead use the slit centres (and lengths) in the Input Object list and thus extract two-dimensional spectra from the raw images. An external source-finding algorithm could then be used to extract one-dimensional spectra of all the objects within the individual slits. Of course, the aXe software can also be used in the normal configuration if, as in the case of the GOODS survey, the object positions are accurately known.

In order to derive a global calibration for FORS2 and the 300I grism used for the GOODS survey, we have obtained through-slit, flat-field and wavelength exposures with a special calibration mask in daytime. This mask features 47 slits uniformly covering the typical area of science slits. The main calibrations needed for aXe are the trace and wavelength solution as a function of the reference position. To derive the trace calibration, all object traces were determined on the flat-field exposures. The traces over the FoV can be reasonably well approximated by a field-dependent second-order polynomial yielding residuals of less than 0.15 pixel rms (1 pixel corresponds to 0.25 arcsec on the sky). See Figure 2 for an example.

Using the trace solution we have examined arc-lamp exposures obtained with our special calibration mask to derive a global wavelength solution. Here a field-dependent 4th-order polynomial fit is needed to describe individual wavelength solutions with a typical rms of 0.13 Å.

As a check of our global wavelength calibration we compared the predicted wavelengths with arc-lamp observations taken through a science mask during daytime. Furthermore, we compared our wavelength predictions with the observations of relatively isolated and strong night skylines with known wavelength. The systematic errors in the mean, absolute wavelength scale appear to be generally less than 0.1 nm, and may be reduced even further by adopting global shifts based on measurements of skylines. More importantly, wavelength-dependent errors also appear to be small (< 0.1 nm), except perhaps at wavelengths shorter than 600 nm where the error may reach 0.2 nm. Note that the average dispersion is 0.32 nm/pixel.

The quality of our trace and wavelength predictions can be best demonstrated when running the aXe software in a mode in which two-dimensional spectra are extracted. In this mode, fully-calibrated and rectified spectra are produced for each slit on the science mask. An example of this is shown in Figure 3 in which we addition ally apply a simple background removal procedure.

Since aXe was initially designed for slitless spectroscopy data, the assumption is made that any pixel can receive a spectral element from any wavelength over the sensitive range of the detector and spectral elements. Thus in order to apply a pixel-flat-field correction (a P-flat in HST terminology), the wavelength dependence of the flat field for each pixel must be determined. For the ACS this was performed by fitting the wavelength dependence, pixel-by-pixel, of flat fields taken with the available filters (for details see Walsh & Pirzkal 2005). The flat field used by aXe is a polynomial fit to the wavelength dependence of these flat fields; the flat field is then stored as a flat field cube with each plane holding the coefficient of the polynomial fit per pixel. An identical procedure was implemented for FORS2.

Required modifications to aXe

Some additions to aXe had to be implemented in order to reduce FORS2-MXU data. The additions mostly deal with the "special" needs of slit spectroscopy

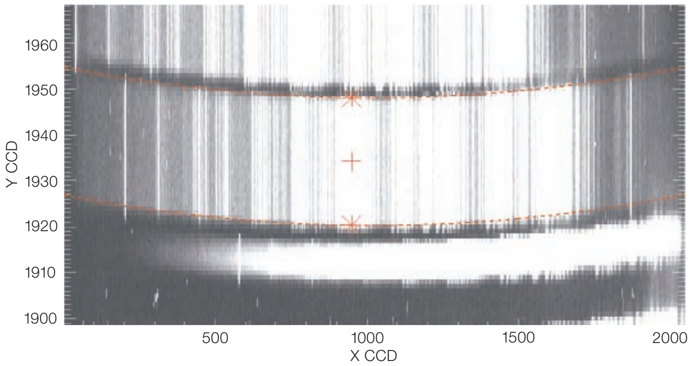


Figure 2: An example of our trace predictions (orange dashed lines) for an individual slit in CCD coordinates. The plus sign marks the projected slit centre and the star symbols indicate the projected slit edges.

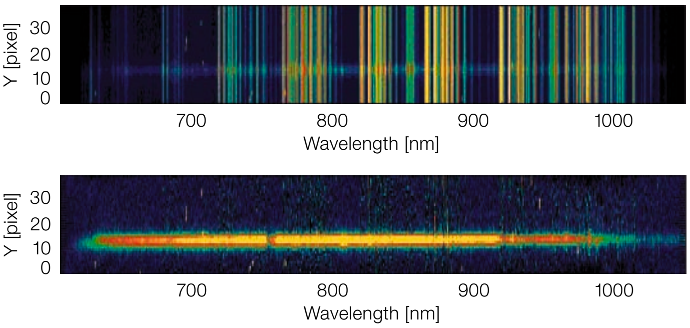
and ground-based astronomy, but do not touch aXe core parts. (a) In contrast to ACS slitless spectroscopy the finite length of slits limits the useful area for background determination. Furthermore, the background estimator in aXe had to include cosmic-ray detection and rejection, which is done prior to running aXe on ACS data. (b) The production of a science-ready two-dimensional spectrum for each slit was introduced. This allows the user to check results and fine-tune parameters. These intermediate products can even be used as starting points for data reduction with other software packages such as IRAF (see also Figure 3). (c) The possibility to extract spectra from significantly bent traces such as in FORS2-MXU also had to be added.

Comparison with GOODS “by hand” extraction

In order to verify the quality of our aXe data reduction, we compared our one-dimensional spectra with the GOODS team “by-hand” extraction[1]. The test data set consisted of 12 individual exposures (total = 14 400 s) taken with one mask. Each of the science exposures was treated separately, and by driving the aXe software with accurate object coordinates, one-dimensional spectra for all objects on the mask were produced. Finally the one-dimensional spectra of the individual objects were combined using a sigma-clipping algorithm.

Figure 4 compares a subset of our spectra with the ones extracted by the GOODS team. The overall agreement between the aXe and GOODS team data reduction is good. We recover all important emission and absorption lines, which are used to determine the redshift of the objects. However, there are sometimes significant differences in the line strength of emission lines. We note that in the aXe reduction the individual one-dimensional spectra were median scaled before combination, while the GOODS team combines the spectra with a weighting according to spectral quality and seeing.

Figure 3: Top: The fully calibrated and rectified two-dimensional spectrum for one 20-min exposure of one slit from the GOODS/FORS2 test data set as produced by aXe is shown. Night skylines largely dominate the signal. **Bottom:** The same spectral region after the application of a simple background removal procedure. A clear signature of a continuum source is visible. Note that for demonstration purposes the y-axis is heavily stretched.



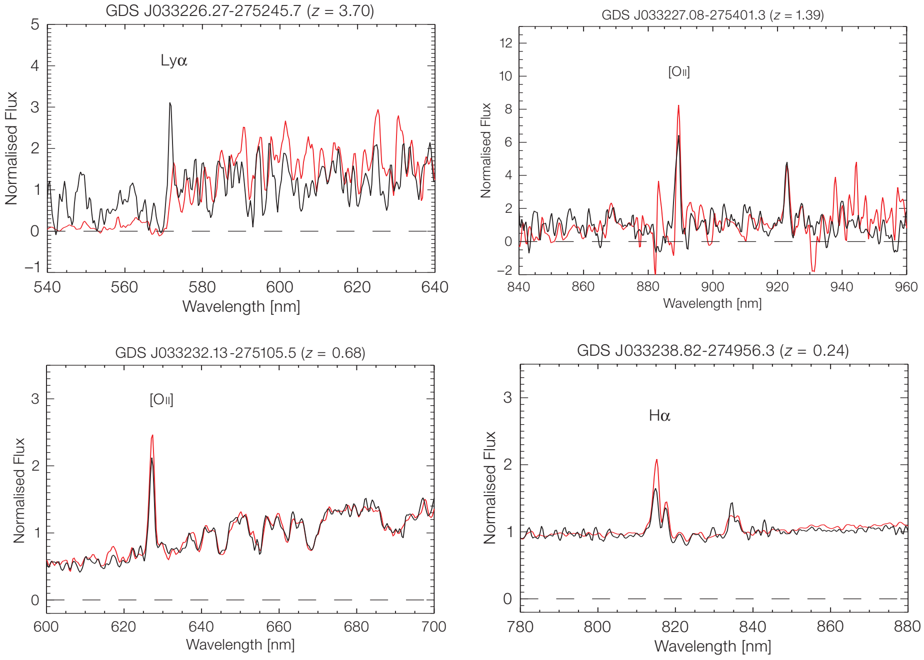


Figure 4 (below): A comparison with the GOODS team ”by hand” reduction for four galaxies spanning a range in red-shift from 0.24 to 3.70. The black solid line represents the GOODS team spectrum, the red line the aXe reduction.

The different scaling methods and cosmic-ray-rejection algorithms may account for some of the differences.

Concluding remarks

In this feasibility study we demonstrate that the current implementation of aXe can successfully extract one-dimensional spectra from FORS2-MXU data of the GOODS survey. Although the reduction process is largely unsupervised we can produce spectra of similar quality to the “by hand” reduction of the GOODS team. There are significant tasks to be carried out before the software reaches the maturity of a common-user reduction package, for example, trending of the trace and stability of the wavelength solution for various grisms. Furthermore there are a number of reduction steps which require improvements such as catalogue generation and determination of reference position for each FORS2-MXU spectrum. We encourage astronomers who are interested in the application of this software to FORS2 to contact us (email: *stdesk@eso.org*) and let us know what demands their data would require of our software.

References

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[1] We are grateful to the GOODS team for early access to the spectra.