Slitless spectroscopy with the Advanced Camera for Surveys

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**Abstract.** The Advanced Camera for Surveys (ACS) enables low resolution slitless spectroscopic imaging in the three channels. The most-used modes are grism imaging with the WFC and the HRC at a resolution of 40 and 24 Å/pixel, respectively. In the far UV there are two prisms for the SBC and a prism for the HRC in the near-UV. An overview of the slitless spectroscopic modes of the ACS is presented together with the advantages of slitless spectroscopy from space. The methods and strategies developed to establish and maintain the wavelength and flux calibration for the different channels are outlined. Since many slitless spectra are recorded on one deep exposure, pipeline science quality extraction of spectra is a necessity. To reduce ACS slitless data, the aXe spectral extraction software has been developed at the ST-ECF. aXe was designed to extract large numbers of ACS slitless spectra in an unsupervised way based on an input catalogue derived from a companion direct image. In order to handle dithered slitless spectra, drizzle, well-known in the imaging domain, has been applied. For ACS grism images, the aXedrizzle technique resamples 2D spectra from individual images to deep, rectified images before extracting the 1D spectra. aXe also provides tools for visual assessment of the extracted spectra and examples are presented.

1. Grisms and prisms on the ACS

The ACS has three channels, the Wide Field Channel (WFC), the High resolution Channel (HRC) and the Solar Blind Channel (SBC), and each channel is capable of delivering slitless spectroscopic images by inserting a grism or prism into the optical beam. The five different combinations of ACS channel and dispersing element offer low resolution spectroscopy from the UV to the far-red wavelength regime. Table 1 lists important parameters such as spectral resolution, wavelength range and field of view (FoV) for all slitless modes of ACS.

| Channel | Disperser | Wav. Range [Å] | Resolution [Å/pixel] | Pixel Size [mas/pixel] | FOV [arcsecond] |
|---------|-----------|----------------|-----------------------|------------------------|-----------------|
| WFC     | G800L     | 5500 – 10500   | 38.5                  | 50 × 50                | 202 × 202       |
| HRC     | G800L     | 5500 – 10500   | 23.5                  | 28 × 24                | 29 × 26         |
| HRC     | PR200L    | 1700 – 3900    | 20[@2500Å]            | 28 × 24                | 29 × 26         |
| SBC     | PR130L    | 1250 – 1800    | 7[@1500Å]             | 34 × 30                | 35 × 31         |
| HRC     | PR110L    | 1150 – 1800    | 10[@1500Å]            | 34 × 30                | 35 × 31         |

Table 1.: The spectroscopic modes of the ACS.

Figure illustrates the differences of using grisms and prisms as dispersive elements by comparing the dispersion and the sensitivity of the HRC grism G800L (left) and the HRC prism PR200L (right). The G800L has an almost constant dispersion over the entire accessible wavelength range. The dispersion of the PR200L increases drastically towards longer...
The different properties of the prisms and grisms require a flexible data reduction software to be able to reduce both slitless grism and prism data.

Following the demise of STIS in August 2004 the interest in using ACS grisms and prisms has increased substantially, since it is the only optical-UV spectral capability aboard HST. As a result, around 10% of all approved orbits in Cycle 14 are devoted to slitless spectroscopy mode with ACS (Macchetto et al. 2005).

2. Slitless spectroscopy from space

Slitless spectroscopy with the ACS has some distinctive features which clearly separate the technique from spectroscopy with slits. Its advantages are:

- The sky background is extremely low. Typical background count rates for the combinations WFC/G800L, HRC/G800L and HRC/PR200L are 0.1, 0.006 and 0.04 $e^{-}/s/pix$, respectively. With typical exposure times in the range 1000–2000 s the read-out noise of $\sim 4.9e^{-}$ remains an important to even dominant source to the overall noise in the images.

- In contrast to the ground-based sky background, which is usually dominated by emission lines, the HST sky background is much smoother, which makes the background removal less problematic. Since the removal of a background with emission lines always leaves variations in the signal-to-noise ratio and therefore leads selection effect in the analysis of the data. ACS slitless spectroscopy avoids these selection effects.

- ACS slitless spectroscopy is associated with an extremely large data yield. To illustrate this Figure 2 displays a MultiDrizzle-combined WFC/G800L image. While it is not
Figure 2.: A MultiDrizzle-combined WFC/G800L image. The large number of spectra to be extracted from the data and the mutual contamination of spectral orders are evident.

general to extract slitless spectra from MultiDrizzle-combined images such as Fig. 2, such coadded images give a first impression on what can be expected from the data. The image shows the spectra of thousands of objects, which all can be extracted from the data. In ACS slitless spectroscopy, the number of objects per field to be extracted is solely determined by the depth of the observation.

- Also the typical advantages of the HST, such as the compact point spread function and the high stability of the instrument, apply to ACS slitless spectroscopy.

The disadvantages of the ACS slitless spectroscopy modes are:

- The mutual contamination of spectra is an ubiquitous phenomenon in slitless spectroscopy, especially since the absence of slits or masks allows a contamination in the spectral direction (see Fig. 2). The contamination can occur even from higher spectra orders. In Fig. 2 this becomes evident when looking at the various spectral orders of the bright stars, which cover a large area and of course overlay the spectra of the fainter objects. Contamination affects all spectra to various degrees, and the reduction software has to deal with contamination (see Section 5 and Walsh, Kümmel & Larsen 2005).

- The reduction of slitless spectroscopic data is quite different from the usual extraction of spectra taken with slits. It requires different methods, the application of different
4

Figure 3.: The HRC/G800L grism image (right panel) and the associated direct image taken with the F555W filter (left panel). The reference point for an example object is determined with SExtractor in the F555W image and then transferred to the G800L image. In the grism image the reference point is the origin of the coordinate system to describe the location of the trace. Finally, the wavelength solution is applied as a function of the trace length.

...calibrations and the usage of different software. As a consequence, the astronomer needs some time to get familiar with slitless data and its reduction concepts.

3. Reducing slitless spectroscopic data

In ‘traditional’ spectroscopy with slits, the aperture (slit or mask) defines a framework for the trace definition and the wavelength solution. The information derived from calibration data (flatfield- and arc-exposures) taken with the identical instrumental setup is directly transferred to the science data to extract the spectra.

In slitless spectroscopy, however, such a framework does not exist. The exact location of the objects on the science data is unknown, and it is impossible to establish a trace description and a wavelength solution on the basis of slitless data alone such as in the right panel in Figure 3. To base a framework or coordinate system for the trace description and wavelength solution, a so-called reference point is needed for every spectrum which is to be extracted. The reference point is the basis for the origin of a local coordinate system (see Fig. 3 right panel) to define the trace description and apply the wavelength solution. In ACS slitless spectroscopy, the reference points of all objects are established on a direct image such as shown in Fig. 3 left panel, which is associated with every slitless image. Then the extraction procedure is as follows:

1. All object positions and therefore reference points are determined on the direct image, which was taken very close on time to the slitless image. This is done either directly with a source detection software such as SExtractor, or indirectly by computing their pixel coordinates on the direct image. (left panel in Fig. 3).

2. The reference positions are transferred to the slitless image (right panel in Fig. 3).

3. A so-called aXe configuration file, which was assembled using calibration data (see next Section), gives the prescription to define the trace description and the wavelength solution for every reference position on the slitless image.

4. The object spectra are finally extracted from the slitless image.
Figure 4.: Left panel: The spectrum of the Wolf-Rayet star W45, which was used to establish a wavelength calibration for the WFC/G800L mode. Right panel: The positions of astronomical targets across the WFC/G800L FoV to determine the 2D-dependence of the calibrations.

4. The calibration of the slitless modes

The main calibration products acquired for an ACS slitless mode are:

- The aXe configuration file to describe trace description and wavelength solution.
- A sensitivity file for the flux calibration of every spectral order.
- A flatfield to be able to apply pixel-to-pixel gain corrections.

Since there are no on-board calibration lamps for ACS, suitable astronomical targets with known fluxes and known spectral features were observed in dedicated calibration proposals to establish the flux calibration and wavelength calibration, respectively.

For the flux calibration and trace definition, white dwarf standards could be used for all ACS slitless modes. For the wavelength calibration, planetary nebulae and Wolf-Rayet stars were observed for the optical modes WFC/G800L and HRC/G800L (Pasquali et al. 2005, Larsen & Walsh 2005). The left panel of Figure 4 shows the first order spectrum of the Wolf-Rayet star WR45 as observed with the WFC/G800L. The bright emission lines which spread over the entire spectral range are identified to define the wavelength solution. The ACS prism modes, which cover the near-UV (HRC/PR200L, SBC/PR120L and HRC/PR110L), were wavelength calibrated using observations of planetary nebulae and carefully redshift-selected QSO’s (Larsen, Kümmler & Walsh 2005).

In all ACS slitless modes, the trace definition, wavelength calibration and sensitivity show variations across the FoV. For this reason the astronomical calibration targets are observed at several positions across the FoV. Figure 4 shows as an example the positions of the astronomical calibration targets across the WFC FoV. After establishing the calibration at each position individually, a global 2D solution is fitted to the individual solutions, which then enables to derive the calibration at every arbitrary position in the FoV.
Figure 5.: The structure of a flatfield cube. Each extension of the fits file gives the coefficients to compute the flatfield correction for every pixel.

The absence of on-board calibration lamps also inhibits the conventional approach for flatfielding. But even if calibration lamps were present, taking a flatfield exposure for every science exposure, as it is usually done in slit spectroscopy, could not deliver a proper flatfield. In ACS slitless spectroscopy the objects and their exact position, and therefore the wavelength attributed to the pixels, are unknown prior to the data reduction. Moreover there are several wavelengths associated to each pixel in regions where the spectra of multiple objects overlap, and this is not possible in the conventional approach.

As a consequence, the flatfield used in ACS slitless spectroscopy must be able to correct any pixel for any wavelength. The solution to this problem is a flatfield cube, as shown in Figure 5. A flatfield cube is a multi-extension fits file, and every extension contains the coefficients to compute the gain correction for any given pixel $(i, j)$ at any wavelength $\lambda$ according to the formula:

$$FF(i, j, \lambda) = a_0(i, j) + a_1(i, j) \cdot \lambda + a_2(i, j) \cdot \lambda^2 + a_3(i, j) \cdot \lambda^3 \ldots$$

The flatfield cubes for the different spectroscopic modes are created from photometric flats, and further details on the flatfielding is given in Walsh & Pirzkal (2005).

5. The aXe spectral extraction software

The aXe software package was specifically designed to extract spectra in a consistent manner from all slitless spectroscopic modes of the ACS. While the reduction of slitless spectroscopic ACS data was the driving force behind the development of aXe, the software package was designed to allow also the reduction of spectroscopic data from other instruments without need for fundamental software changes, and currently an investigation is done to apply aXe to data taken with the FORS2-MXU unit at the VLT (see Küemmel et al. 2006 and Kuntschner et al. 2005).

aXe is a PyRAF/IRAF package with several tasks (see Figure 6) which can successively be used to produce extracted spectra from slitless data. As can be seen in Fig. 6, there exist two classes of aXe tasks:

1. The Low Level Tasks work on individual images. Their aim is to perform a certain reduction step on a particular image.
2. The High Level Tasks work on data sets. Their aim is to do a sequence of processing steps on several images.

Often the High Level Tasks call Low Level Tasks to perform a certain reduction step on individual images, and Fig. 6 shows their interaction. The High Level Tasks were designed to cover all steps of the aXe data reduction, and working with aXe usually means to apply the High Level Tasks to data sets. Due to the large data yield in ACS slitless data, which makes it impossible to extract every spectrum individually, aXe is built as a semi-automatic data reduction system. After the object positions are determined on the direct images (see Sect. 3.), aXe runs automatically and creates besides the final, extracted spectra additional intermediate products, such as 2-dimensional stamp images of the spectra. The intermediate data products help the user to check the reduction procedure and to fine-tune the extraction parameters.

The aXe tasks are implemented in Python. To work on the pixel data (such as flatfielding or extracting 1D spectra), which requires a large computational speed, the Low Level Tasks call executables which are implemented in standard C. Via PyRAF the aXe tasks are fully embedded into the STSDAS software package, and aXe users do not have to leave their familiar data reduction environment to work with ACS slitless data. The aXe package evolves continuously, and together with STSDAS new aXe versions are released about once a year. The current aXe-1.5 was released together with STSDAS 3.4 in November 2005. Between these large releases there are occasional smaller software releases via the aXe webpage [http://www.stecf.org/software/aXe/] to publish bug-fixes or together with new aXe configuration files.

The two main drivers behind the development of the aXe software package are:

1. Improvements for the user convenience.

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**Figure 6.** The list of aXe tasks. The arrows indicate the interaction between the High Level and the Low Level Tasks. The right column describes the reduction step executed by a certain task.
Figure 7.: The aXedrizzle method of combining 2D spectra. The object in panel a is extracted as a stamp image (b), which is drizzled to an image with constant dispersion and constant pixel scale in spatial direction. The 1D spectrum is finally extracted from the deep, coadded 2D spectrum (d).

2. Adding new functionality to aXe.

The former was the motivation for developing the High Level Tasks in aXe-1.4, which greatly reduced the number of commands with which the user has to become acquainted. In aXe-1.5 the task `iolprep` was added, which is a new tool to generate SExtractor lists with object positions for a set of slitless images in a standard scenario.

As new functionality `optimal weighting` and the so-called `quantitative contamination` were added in aXe-1.5. The old aXe method of recording contamination associates to every pixel in the slitless image the number of spectra of which the pixel is a part. This information is processed in the 1D spectral extraction, and each spectral element has as contamination information the number of other spectra its input pixels contributed to. This method of recording contamination gives no clue on how much the contaminating objects actually influence the extracted object flux.

In quantitative contamination the contributing flux from other objects to every spectral bin is estimated according to a simple emission model. The quantitative contamination estimate is a very good tool for the user to decide which data points he can trust. A detailed description of the quantitative contamination method and of the optimal weighting implemented in aXe-1.5 is given in Walsh, Kümmel & Larsen (2005).

Another important addition to the functionality of aXe is the `axedrizzle` method, which was first released in aXe-1.4 (Kümmel et al. 2005). With the aXedrizzle method the individual 2D spectra of an object (see Figure 7a, b) are coadded to a single, deep 2D image (Fig. 7d) before extracting the 1D spectrum. The combination of the individual 2D spectra is done with the “Drizzle” software (Fruchter & Hook 2002), which is well known from HST imaging. This method of combining the data has several advantages:

- Resampling to a uniform wavelength scale and an orthogonal spatial direction with a constant pixel scale is achieved in a single step.
Figure 8.: A webpage created by aXe2web. The various rows contain information on individual objects such as their reference number, magnitude, position, stamp images and spectra.

- Pixel weighting is handled correctly.
- The coadded 2D spectrum can be viewed to detect problems.

Due to the highly non-linear form of the prism dispersion (see Fig. 1), the aXedrizzle method is restricted to the ACS grism modes WFC/G800L and HRC/G800L only.

6. The aXe visualisation of spectra

As indicated above, a data set with ACS slitless images may contain hundreds or even thousands of spectra, and a visual inspection of each individual spectrum is very tedious. To help the user digest the large amount of data, the tool aXe2web was implemented, which produces browsable webpages for a fast and discerning examination of spectra (Walsh & Kümmel 2004).

aXe2web uses the direct image, the SExtractor catalogue, the aXe stamp images and the extracted spectra to produce an HTML summary containing a variety of information for each spectrum. Figure 8 shows part of an HTML page produced by aXe2web. Each object produces a line in the HTML page which lists the sequence number, the reference number, the magnitude of the direct image object, the coordinates (image and RA/DEC) of the direct image object, the direct stamp image, the grism/prism stamp image and the 1D extracted spectrum in counts/s and flux.

To facilitate an easy navigation within a data set, an overview and an index page accompany the object pages (Fig. 8) which show the detailed object information. The overview page contains for each object the basic information, e.g. object positions and...
Magnitudes, and the index page includes a table with the ordered reference numbers of all objects. Direct links guide from the overview page and the index page to the corresponding location on the object pages.

7. Conclusions

- All aspects of ACS slitless spectroscopy (calibration, software etc.) are supported such that users can obtain and reduce slitless data in a pipeline way.
- ACS slitless spectroscopy is successfully used in various science projects such as the HUDF HRC Parallels (Walsh, Kümmel & Larsen 2004), high redshift supernovae research (Riess et al. 2004) and the search for high redshift galaxies (the GRAPES and PEARs programmes, see Pirzkal et al., 2004).
- More information about ACS slitless spectroscopy, the calibration and the aXe software is given on the aXe webpages at [http://www.stecf.org/software/aXe/](http://www.stecf.org/software/aXe/)
- User support concerning all topics related to ACS slitless spectroscopy is provided by the ACS group at the Space Telescope - European Coordinating Facility (ST-ECF). The centralised email address for requests is acsdesk@eso.org.

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