Squeezing Together: A New Procedure for Extracting Spectra at the Third COS/FUV Lifetime Position

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Introduction

The micro-channel plates of the Cosmic Origins Spectrograph (COS) far-ultraviolet (FUV) detector have a limited lifetime. A high voltage gradient across the detector's micro-channel plates (MCPs) creates a cascade of electrons in response to each detected FUV photon. However, only so many electrons can be extracted from a given location of each MCP, and once a given detector pixel has been exposed to about 2.7×10^4 photons, the number of electrons produced per photon, i.e., the gain, gets too low to reliably locate the original photon.[1] This localized "gain sag" on the MCP makes it necessary to adjust the COS FUV aperture locations and *Hubble* pointing every few years to shift the spectra to a fresh part of the detector. These adjustments are referred to as "Lifetime Position" moves.

As detailed in the accompanying article by Roman-Duval et al., the second such move, from Lifetime Position 2 (LP2) to Lifetime Position 3 (LP3), was made on February 9, 2015. At current usage rates, each Lifetime Position should give good quality data for about 2½ years. Up to five total positions are potentially available. This should allow the COS FUV channel to continue operation well past 2020 with only minor compromises in its performance.

To maximize spectral resolution and the lifetime of COS, it was decided to locate LP3 at a location as close as possible to the original LP1 position. An offset from LP1 of only –2.5'' was adopted, significantly smaller than the +3.5'' offset adopted for LP2. Because this places new spectra very close to the worn-out regions near LP1, it complicates the extraction of 1D spectra from the 2D spectral images.

The COS detector format is long and narrow, with each of the two detector segments being divided into 16,384 pixels in the *X* or dispersion direction, but only 1024 in the *Y* direction perpendicular to the dispersion. When a spectrum of an external point-source target is taken, the 2D spectral image occupies only a small part of this vertical range (typically less than 30 pixels in the cross-dispersion direction). The exact location and height of the footprint of each COS mode on the detector vary with the grating and central wavelength setting, (as shown in Figure 1).

To extract the flux observed at each wavelength, it is first necessary to sum the detected counts at each wavelength (*X* location), over the illuminated cross-dispersion profile (*Y* direction). For a given central wavelength setting, the older "BOXCAR" extraction algorithm, which COS uses for data taken at LP1 and LP2, adopts a fixed extraction region that is generously sized to include all of the flux from a point-source target even after allowing for typical centering errors in the aperture. If any "bad" pixels at all are included in the region being used for the sum, the entire column is marked as bad and these regions are excluded when combining different exposures.

At the new LP3 position, this can create problems, as illustrated in Figure 1. The overlap of the large

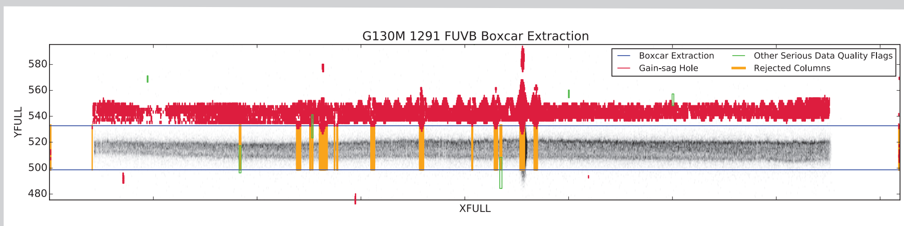

Figure 1: This illustrates how the BOXCAR algorithm would operate at LP3. The grayscale image shows the observed distribution of light on the FUVB detector segment for an observation of a hot standard star done using the 1291 setting of the COS G130M grating. The wavelength increases with the XFULL coordinate, while YFULL is the spatial direction perpendicular to the dispersion. The red regions show the areas of the detector damaged from earlier usage. The blue lines mark the edges of the region used in the BOXCAR extraction. At any location where the bad pixels fall in between the blue lines, the entire wavelength bin is flagged as bad. These regions are marked in yellow. As can be seen here, many wavelength bins are being rejected for rather minor overlap with the damaged regions.

[1]Note that the COS NUV and the STIS FUV and NUV Multi-Anode Micro-channel plate Array (MAMA) detectors use crossed sets of anode wires to detect and locate events. This allows them to operate at significantly lower gain than does the long-format COS FUV delay line detector. Because of this design difference, degradation from gain sag is not expected to be a concern during the lifetime of the MAMA detectors.

extraction box with the previously damaged regions of the detector can result in several wavelength bins being discarded. However, the LP3 location was chosen so that these bad detector regions fall at the edge of the spectral profiles, where the loss of flux is negligible (see article by Roman-Duval). What is therefore needed is an algorithm that can decide when a "bad" pixel impacts the profile enough that it might significantly compromise the measured flux.

The new extraction procedure

The new TWOZONE extraction algorithm was developed for this purpose. The observed spectral image is first straightened by a new calibration step to remove residual optical and detector distortions in the cross-dispersion direction (see Fig. 2) and then shifted in the cross-dispersion direction to align with a point-source template reference profile (see Fig. 3). This reference profile is then "shrink-wrapped" to define two different regions for the extraction—an "inner" zone containing about 80% of the enclosed profile energy and an "outer" zone containing about 99% of the enclosed energy (see Fig. 4). The observed counts are summed over the full 99% enclosed energy region, but columns are rejected only if bad pixels are found in the inner zone.

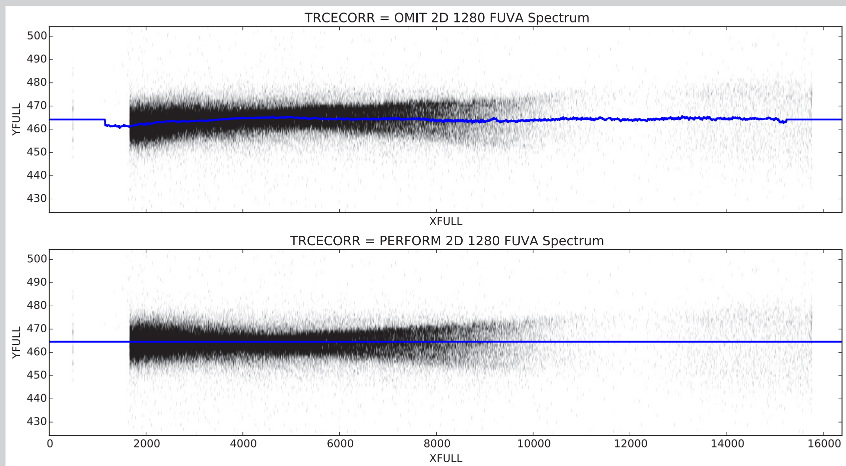

Figure 2: This figure shows how the new distortion correction in the revised algorithm removes optical and detector distortions, yielding a straighter spectrum that is easier to compare and align with reference profiles. The *top* panel shows the uncorrected spectral image for a G140L 1280 FUVA observation, while the *bottom* panel shows the image after the correction has been applied.

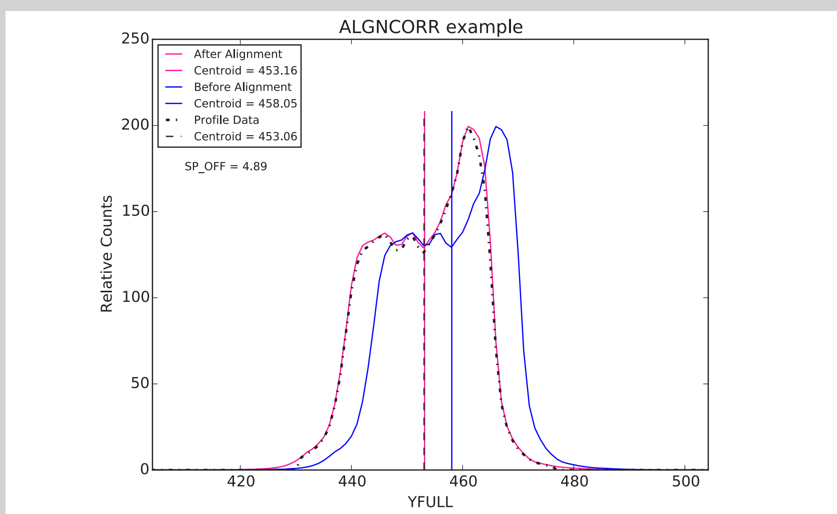

Figure 3: This figure shows the collapsed cross-dispersion profile, summed over all wavelengths, of a G130M 1222 FUVA observation before (blue line) and after (pink line) the data have been aligned. For COS FUV observations, each pixel in the cross-dispersion direction corresponds to about 0.1'' on the sky. The broken line shows the collapsed cross-dispersion reference profile to which the observed profile was aligned. The flux-weighted centroid values for each of the profiles are also marked by a vertical line.

A library of standard reference profiles, one for each of the available central wavelength settings, has been tabulated and is included with the reference files used to calibrate COS data. Using the reference template profiles rather than the observed data from each individual observation to define the inner and outer zones allows reliable calibration for even very faint and noisy observations. Another reference file contains the library of residual distortion corrections used to straighten the images prior to alignment with the profiles. This correction not only results in smoother profiles, but it ensures that the centering in the cross-dispersion direction is done consistently, regardless of the shape of the source spectral energy distribution.

In Figure 5, we show how this new algorithm is applied to the data shown in Figure 1. The columns are only rejected when a pixel in the inner 80% of the enclosed energy is marked as bad. This dramatically reduces the number of gaps in the extracted 1D spectrum without leading to the introduction of any artifacts from the gain-sag holes.

In the absence of bad detector regions, and when observing point sources, the new algorithm gives results very close to that of the old BOXCAR algorithm. If, instead of developing the TWOZONE algorithm, we had simply adopted a smaller BOXCAR extraction region and corrected the flux for the reduced enclosed energy fraction, the results would have been unacceptably sensitive to minor misalignments of the source profile with the narrow extraction region. Summing over the 99% enclosed energy region of the spectral image allows the TWOZONE algorithm to be tolerant of such minor misalignments or changes in the profile's shape. Another advantage of the new algorithm is that by reducing the height over which spectra are extracted, the amount of detector background included is also reduced. This will improve the signal-to-noise for observations of very faint sources.

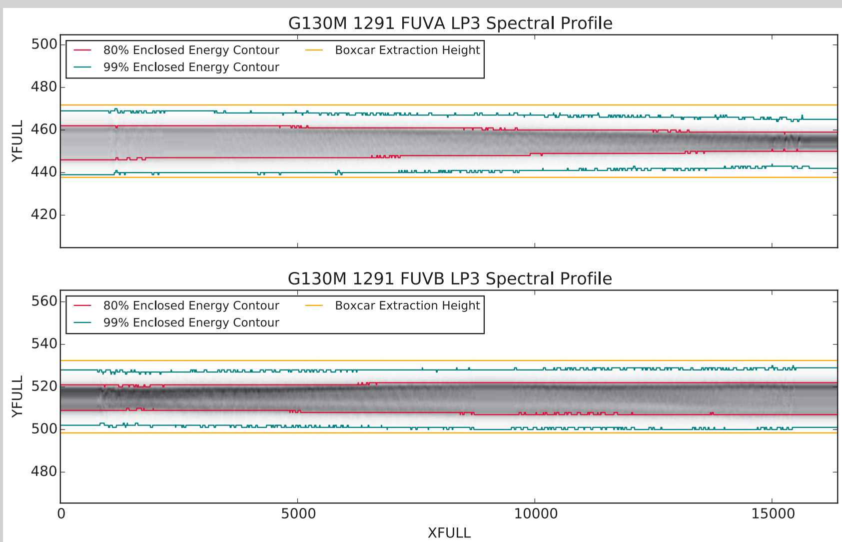

Figure 4: The point-source template reference profiles for both the FUVA (*top*) and FUVB (*bottom*) segments of the G130M 1291 setting at LP3 are shown by the grayscale images. Three sets of contours are also shown. The outermost yellow contours approximate the extraction region used in the BOXCAR algorithm. The blue curves mark the 99% enclosed energy contour, while the red curves show the 80% enclosed energy contour.

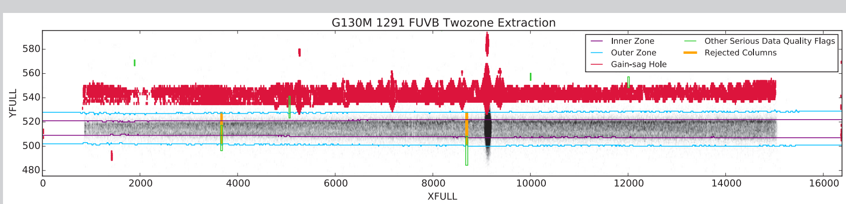

Figure 5: This figure illustrates the application of the new TWOZONE extraction algorithm. The annotations are as in Figure 1, except that instead of marking the large extraction region used for the BOXCAR algorithm, we show the boundaries of the inner (pink line, 80% enclosed energy) and outer (blue line, 99% enclosed energy) zones used in the TWOZONE extraction algorithm. Note that when using the TWOZONE algorithm, there are far fewer rejected regions (yellow) then there are when using the BOXCAR algorithm (Fig. 1)

Because the new extraction region is narrower in the cross-dispersion direction than is the region used by the BOXCAR algorithm, the results for spatially extended sources calibrated using the TWOZONE algorithm may show larger artifacts than would have been the case for the older algorithm. Sources with an angular diameter larger than about 0.6 arcseconds may require a customized extraction to yield the best results.

This new TWOZONE extraction algorithm is currently being used by default for calibration of all COS FUV data taken at LP3, and is applied to all such data retrieved from the Milkulski Archive for Space Telescopes (MAST). Data from earlier lifetime positions continue to be calibrated using the BOXCAR algorithm. Full details are given in Instrument Science Report COS ISR 2015-02 by Proffitt et al., which is available on the COS instrument web pages, and in version 3.0 of the *COS Data Handbook* (Fox et al. 2016).