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Spectral Extraction of the New COS/FUV G160M/1533 Mode: Extraction, Trace, and Profile Reference Files

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ABSTRACT

We describe the creation of the reference files used in the BOXCAR and TWOZONE extraction algorithms for the new COS/FUV central wavelength setting G160M/1533. We observed the bright white dwarf standard stars WD 0308–565 and GD 71 with Program 15458 in 2018 June and August, respectively. We analyze the 2-D profile and spectral trace on each segment of the detector in order to derive the entries for the 1-D spectral extraction, trace correction, profile, and TWOZONE spectral extraction reference files. The files were tested for scientific accuracy, and then delivered to the reference file database system in 2018 November for use in the COS calibration pipeline.

Contents

1. Introduction

The Cosmic Origins Spectrograph (COS) team introduced two new central wavelength (cenwave) settings for the far ultraviolet (FUV) detector starting in Cycle 26: G160M/1533 and G140L/800. G160M/1533 was designed to extend the wavelength coverage of the G160M grating to shorter wavelengths by 44 Å, making it overlap with the longer-wavelength end of the G130M/1222 observing mode. This means that broad FUV wavelength coverage can be achieved using just the two aforementioned medium-resolution observing settings. This, along with the fact that Lyman α falls in the detector gap in the G130M/1222 mode, helps extend the lifetime of the COS/FUV detector. In this Instrument Science Report (ISR), we document observations, calibrations, and analyses that led to the creation of the reference files used by the COS calibration pipeline, CalCOS, to perform the spectral extraction of G160M/1533. This ISR is a part of a collection of ISRs that documents the full calibration of the G160M/1533 cenwave: the focus position (James et al. 2019a), the lamp template (James et al. 2019b), the wavelength calibration (Fox et al. 2019a), and the flux calibration (Fox et al. 2019b).

Spectral extraction for COS/FUV data taken at lifetime position (LP) 3 and beyond can be done in two different ways using either the BOXCAR or TWOZONE methods. The BOXCAR extraction algorithm uses a large rectangular extraction region to collect 100% of the flux from a target. This extraction region is large enough to account for the uncertainty of the centering of the target in the aperture. A downside to this method is that if any pixel in this extraction box has been flagged as bad (such as due to gain sag), then that entire wavelength bin is excluded from the final spectra, even if the pixel in question is at the outer edges of the extraction region where the flux from the target can be very low. The BOXCAR extraction regions are defined by the parameters in the 1-D spectral extraction reference table, the XTRACTAB. More details about BOXCAR extraction and the XTRACTAB can be found in the COS Data Handbook (Rafelski et al. 2018).

The TWOZONE extraction algorithm was created to maintain data quality while allowing separations as close as 2.5" between LP3 and the gain-sagged LP1 region (similarly between LP4 and LP3 gain-sagged regions). This is not possible with BOXCAR extraction since gain-sag holes from LP1 fall within the LP3 extaction box, leading to a large number of wavelength bins being rejected. The TWOZONE algorithm works under the assumption that gain-sagged pixels from previous adjacent LPs will be at the lower or upper edges of the extraction region, and thus will not incur detectable flux losses. Therefore, entire wavelength bins should not be rejected if the bad pixel is in the outer envelope of the spectral profile. The spectral extraction profile is therefore divided into a core inner zone that contains 80% of the profile's enclosed energy and an outer zone that contains 99% of the profile's enclosed energy. These percentages are given in the TWOZONE extraction reference table, the TWOZXTAB, and are the same for all settings at the time of writing this ISR.

The upper and lower boundaries for the inner and outer zones are wavelength dependent and are defined in terms of the fraction of enclosed energy expected for the cross-dispersion profile of a point source. These point-source profiles for each setting are derived from specific calibration observations and are given in the PROFTAB reference file. In order to adequately compare the template point-source profile from the PROFTAB to an observed profile, we also must correct for any small-scale distortions in the cross-dispersion direction that are not removed by thermal and geometric corrections in CalCOS. This is done by creating a spectral trace that flattens the spectral image in the cross-dispersion direction. The corrections for each observing setting are given in the TRACETAB. A detailed account of TWOZONE extraction and its reference files can be found in the COS ISR 2015-03 (Proffitt et al. 2015), as well as in the COS Data Handbook.

This ISR is organized as follows. The observations are described in Section 2, and Section 3 describes how the data are calibrated. We document the creation of each reference file in Section 4, including the XTRACTAB (Section 4.1), the TRACETAB (Section 4.2), the PROFTAB (Section 4.3), and the TWOZXTAB (Section 4.4). The scientific testing procedures for these reference files are detailed in Section 5. Finally, a summary is presented in Section 6.

2. Observations

For this analysis, we observed the bright spectrophotometric white dwarf standard stars WD 0308–565 and GD 71 in the G160M/1533 setting in Program 15458, "COS/FUV G160M/1533 Profiles and Fluxes" (PI E. Snyder). The exposures in this program are a near copy of the G160M/1577 exposures in Program 14910 (PI M. Rafelski), which calibrates all COS/FUV observing modes for spectral extraction at LP4. WD 0308–565 is a continuum source with very few absorption lines and is used as a time-dependent

Table 1. Summary of Special Commanding Used in APT to Observe Data at G160M/1533

Parameter	Value	Description
SPEC COM INSTR	ELOSMTEST	Special commanding instruction
QESIPARM ACTION	TEST	Mode definition
QESIPARM GRATING	G160M	Mode definition
QESIPARM CENTWAVE	1533	Mode definition
QESIPARM STEP1	11218	OSM1 rotation position
QESIPARM RES1	18775	Coarse resolver position
QESIPARM RES2	23405	Fine resolver position
QESIPARM FOCUS4	–646	Focus position of 1533

sensitivity (TDS) target for regular COS/FUV monitoring. As such, it is the primary target for this program and is observed with both segments. GD 71 is used to calibrate FUVA only since it is significantly brighter than WD0308–565 on segment A but would exceed the global count rate limit on segment B. FP-POS 1 and 2 of WD 0308–565 were observed in early June 2018 as Visit 01, and due to a guide star failure, FP-POS 3 and 4 were observed in late June 2018 as Visit 51. All four FP-POS of GD 71 were observed in August 2018 as Visit 02.

Since the G160M/1533 setting was not yet implemented in the Astronomer's Proposal Tool (APT) software at the time the observations were executed, we had to use Special Commanding to observe with this setting. The observations were executed as follows:

1. The target was acquired with an NUV ACQ/IMAGE exposure with the bright object aperture (BOA) and MIRRORA.

2. Special commanding was used to redefine the TEST wavelength setting to the G160M/1533 optical selection mechanism (OSM) rotation position and absolute focus position. The complete set of parameters put into APT to achieve this is given in Table 1. The STEP1, RES1, and RES2 values were determined from ray-trace modeling by S. Penton that computed the wavelength range as a function of OSM rotation. The determination of the focus position is documented in James et al. (2019a).

3. Spectra were obtained at all four FP-POS positions. Exposure times were calculated to give a signal-to-noise of ~ 20 per resolution element, per FP-POS at wavelength 1450 Å for WD 0308–565 or 1625 Å for GD 71. The actual signal-to-noise per observation is larger, since the exposures times were

lengthened in order to fully use the orbits allocated for this program. With all FP-POS co-added, the total Poisson signal-to-noise is well over 50 per resolution element for each segment. Poisson signal-to-noise > 50 is required to ensure that the contours of the profiles can be measured such that the flux errors are less than 1–2%.

4. Special commanding was again used to restore the TEST row using ACTION RESTORE.

The sequence above is the same for both targets, except that segment B is turned off for GD 71. Lastly, we use special commanding in APT to turn off calibration and disassociate the exposures, since the back-end calibration pipeline was not ready to ingest and calibrate the files at the time of execution. We collect these raw data and perform custom calibrations in order to use it in the creation of the new reference files.

3. Calibrations

We calibrate the data used to create the XTRACTAB by first setting the calibration switches in the `rawtag` file headers to those listed in Table 2. In this table, the steps listed in black have been changed from their default values, which are described next. We first change the RANDSEED value to be the same for all `rawtag` files, which is useful for testing later. We set the extraction algorithm to be BOXCAR and set TRCECORR and ALGNCORR (steps in CalCOS used for the TWOZONE extraction method only) to OMIT. We turn off DOPPCORR, under the premise that this will not affect the shape of the profile in the cross-dispersion direction significantly. We then turn off most of the calibration steps that happen after the `corrtag` files have been created (HELCORR, BACKCORR, FLUXCORR, BRSTCORR, and TDSCORR), since we will be working primarily with the `XCORR` and `YCORR` columns from the `corrtag` file. We do, however, leave on the wavelength calibration step WAVECORR, so that the `XFULL` and `YFULL` columns of the `corrtag` are correct. We also leave on X1DCORR; although the `x1d` files are not used for the analysis, they are used for later testing.

Since the XTRACTAB is the first reference file created with G160M/1533 entries, the other cenwave-dependent reference files we need for the calibration process will not have the any entries for G160M/1533. As a first order approximation, we created preliminary versions of the LAMPTAB, XTRACTAB, DISPTAB, and SPWCSTAB reference files with G160M/1533 entries that are copies of the G160M/1577 entries. We use the default LP4 reference files for all other calibration steps performed that are not dependent on cenwave (e.g., the FLATFILE, GEOFILE, etc.). Once all of the `rawtag` files have their headers updated with these corrections, we use CalCOS version 3.3.4 to calibrate the data, and we use this to create the final XTRACTAB.

The process is similar for calibrating the data to make the TRACETAB, PROFTAB, and TWOZXTAB reference files. The calibration steps in Table 2 still apply. However, the reference files used are different. The final XTRACTAB is used to

Table 2. Calibration Switches Used to Calibrate Raw Program 15458 Data in CalCOS for the Creation of G160M/1533 Rows for Spectral Extraction Reference Files[1]

Calibration Step	Value	Description
FLATCORR	PERFORM	Apply flat-field correction
DEADCORR	PERFORM	Correct for deadtime
DQICORR	PERFORM	Data quality initialization
STATFLAG	T	Calculate statistics?
TEMPCORR	PERFORM	Correct for thermal distortion
GEOCORR	PERFORM	Correct FUV for geometic distortion
DGEOCORR	PERFORM	Delta Corrections to FUV Geometric Distortion
IGEOCORR	PERFORM	Interpolate geometric distortion in INL file
RANDCORR	PERFORM	Add pseudo-random numbers to raw x and y
RANDSEED	123456789	Seed for pseudo-random number generator
XWLKCORR	OMIT	Correct FUV for Walk Distortion in X
YWLKCORR	PERFORM	Correct FUV for Walk Distortion in Y
PHACORR	PERFORM	Filter by pulse-height
TRCECORR	OMIT	Trace correction
ALGNCORR	OMIT	Align data to profile
XTRCTALG	BOXCAR	BOXCAR or TWOZONE
BADTCORR	OMIT	Filter by time (excluding bad time intervals)
DOPPCORR	OMIT	Orbital Doppler correction
HELCORR	OMIT	Heliocentric Doppler correction
X1DCORR	PERFORM	1-D spectral extraction
BACKCORR	OMIT	Subtract background (when doing 1-D extraction)
WAVECORR	PERFORM	Use wavecal to adjust wavelength zeropoint
FLUXCORR	OMIT	Convert count-rate to absolute flux units
BRSTCORR	OMIT	Switch controlling search for FUV bursts
TDSCORR	OMIT	Switch for time-dependent sensitivity correction

[1]Calibration steps shown in gray are defaults, whereas those in black have been changed from the default.

make the final versions of the LAMPTAB and DISPTAB (detailed in James et al. 2019b and Fox et al. 2019a, respectively), which we can then in turn use in the creation of the final TRACETAB, PROFTAB, and TWOZXTAB. Summarizing, we use the final versions of the XTRACTAB, LAMPTAB, and DISPTAB with the correct G160M/1533 entries for the creation of the TWOZONE reference files. We still use a preliminary version of the SPWCSTAB, since this reference file is not used for the parts of the calibration that we are concerned with in this analysis.

At the time of the creation of the XTRACTAB, only the WD 0308–565 data from Program 15458 had been observed, so they are the only data we analyze for that process. GD 71 is later used for testing of the XTRACTAB. Data from both standard stars are used to create the TRACETAB, PROFTAB, and TWOZXTAB entries for the new cenwave.

4. Reference File Creation

4.1 1-D Spectral Extraction Reference File (XTRACTAB)

The XTRACTAB reference file contains the columns SEGMENT, CENWAVE, APERTURE, SLOPE, B_SPEC, B_BKG1, B_BKG2, HEIGHT, B_HGT1, B_HGT2, and BWIDTH. Brief descriptions of these columns are given in Table 3.9 of the COS Data Handbook. CalCOS uses the XTRACTAB for a number of calibration steps. When XTRCTALG is set to BOXCAR, the spectral extraction is done by collapsing the data within a parallelogram of height HEIGHT that is centered on a line whose slope and intercept are given by SLOPE and B_SPEC. Similarly, for the BACKCORR step, two background spectra are determined by collapsing the data within parallelograms of height B_HGT1 or B_HGT2 centered on the lines defined by SLOPE and B_BKG1, and SLOPE and B_BKG2, respectively. The background spectra are then smoothed by a boxcar of width BWIDTH. The XTRACTAB is also used by CalCOS during the WAVECORR step to determine the SHIFT2 offset between `YCORR` and `YFULL` when using either the BOXCAR and TWOZONE extraction methods.

The XTRACTAB has entries for all four different apertures available on the COS/FUV detector: the Primary Science Aperture (PSA), the Wavelength Calibration Aperture (WCA), the Bright Object Aperture (BOA), and the Flat-Field Calibration Aperture (FCA). The PSA and WCA are most commonly used. The entries for the less-commonly used BOA and FCA apertures are near copies of those for the PSA, except for their background extraction regions. We describe the derivation of the entries for each aperture next.

4.1.1 PSA Analysis

Starting with the calibrated WD 0308–565 `corrtag` files from Program 15458, we create 2-D spectral images in `XCORR` and `YCORR` space. This analysis is performed on the FUVA and FUVB FP-POS = 3 data since this is the nominal FP-POS position for

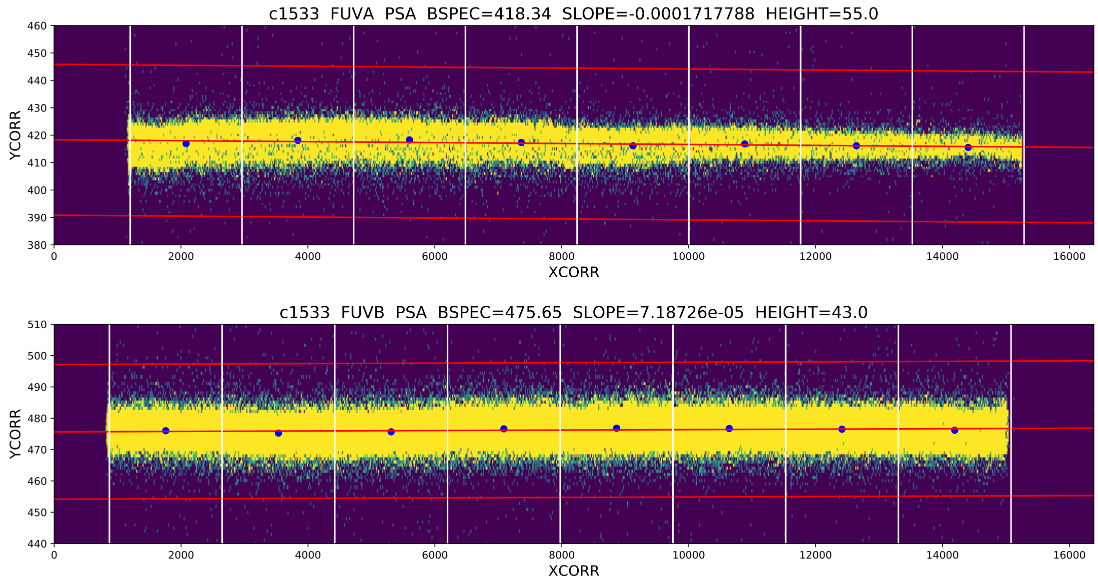

Figure 1. 2-D spectral images of WD 0308–565 FP-POS = 3 FUVA (*top*) and FUVB (*bottom*), which are used to determine the SLOPE, HEIGHT, and B_SPEC values for the G160M/1533 PSA rows in the XTRACTAB reference file. The white vertical lines show the divisions between the eight boxes, and the blue circles show the location of the y-centroid calculated for each box. The central red line is the best fit 1-D line to the blue centroids, and the lower and upper red lines show the lower and upper bounds of the HEIGHT. The final values of the B_SPEC, SLOPE, and HEIGHT for both segments are given in the figure titles.

each cenwave and we have enough signal-to-noise for this purpose from one FP-POS only. We use the other FP-POS data for later testing. We divide the spectral image for each segment into eight equally sized boxes along the dispersion direction. Each box is 100 pixels in height in the cross-dispersion direction and is centered on the flux-weighted centroid of the entire spectral image to ensure that we are enclosing 100% of the target flux. For each box, we sum the counts along the dispersion direction and then subtract the background level from that summed profile. The background level is the average count level along the wings of the summed profile. We then find the y-position of the flux-weighted centroid of the profiles of each box, as well as compute the upper and lower profile extents by finding where 0.25% and 99.75% of the counts are contained. The y-centroids of each box are used to compute the SLOPE and B_SPEC values by fitting along a 1-D line. The HEIGHT is the largest of any of the upper or lower extents found, multiplied by two and then padded by 7 pixels to account for target acquisition offsets. Figure 1 shows the final results of these fits for both segments, including the locations of each box (divided by the white lines), the y-centroids of each box (the blue points), and the middle, lower, and upper boundaries of the extraction regions (the red lines).

The background regions (B_BKG1 and B_BKG2) of segment A of the PSA were modified from those for the G160M/1577 PSA, such that both regions are now above the WCA in order to avoid enhanced dark count regions below the PSA. This work is documented in detail in the COS ISR 2019-11 (Dashtamirova et al. 2019). The background regions for FUVB are the same as those for G160M/1577, with B_BKG1 below the PSA extraction box and B_BKG2 above the WCA extraction box. Figure 2 shows the PSA region, along with the WCA (described next) and the background regions for the PSA for both segments.

4.1.2 WCA Analysis

The process to determine the SLOPE, B_SPEC, and HEIGHT for the WCA is similar to the method for the PSA. However, the wavelength calibration lamp data from Program 15458 does not have the required signal-to-noise for determining all of the WCA extraction parameters, so we instead use high signal-to-noise lamp spectra data from the G160M/1533 Lamp Template program (Program 15459; PI B. James) to calculate the SLOPE and HEIGHT values for the WCA. These data are calibrated as described previously for the Program 15458 data. Similarly as before, we create 2-D images of the FUVA and FUVB FP-POS = 3 data, but we separate it into four bins. Flux-weighted y-centroids of each bin are calculated and used to find the SLOPE, and the upper and lower profile extents are used to calculate the HEIGHT value. Figure 3 shows the 2-D spectral images from Program 15459 and gives the final SLOPE and HEIGHT values. We then use the wavelength calibration lamp data from Program 15458 to find the B_SPEC value only. It is necessary to use the same dataset that was used to derive the PSA B_SPEC value in order to derive the correct offset between the two apertures in the cross-dispersion direction (due to target acquisition offsets). The above process is repeated to find the y-centroids of each box. These are used with the SLOPE calculated previously to compute a final B_SPEC value. The 2-D spectral images from Program 15458 and the final values are shown in Figure 4.

The background boxes for the WCA are the same as for the G160M/1577 PSA, with the exception that on segment A, the lower background box (B_BKG1) is lowered by 5 pixels to avoid overlapping with the G160M/1533 PSA extraction box. Figure 5 shows the placement of the WCA and PSA regions, along with the background regions for the WCA.

4.1.3 BOA and FCA Analysis

The HEIGHT, B_SPEC, and SLOPE values for the BOA and FCA are exact copies of those determined above for the G160M/1533 PSA. For the FCA, the background columns are copies of the G160M/1577 entries. For segment A of the BOA, B_BKG1 is lowered by 8 pixels (to avoid the PSA extraction box) and B_BKG2 is raised by 100 pixels (to avoid airglow). For segment B of the BOA, B_BKG1 is lowered by 8 pixels and B_BKG1 is raised by 80 pixels. Figure 6 shows the BOA with its background regions, and Figure 7 shows the FCA with its background regions.

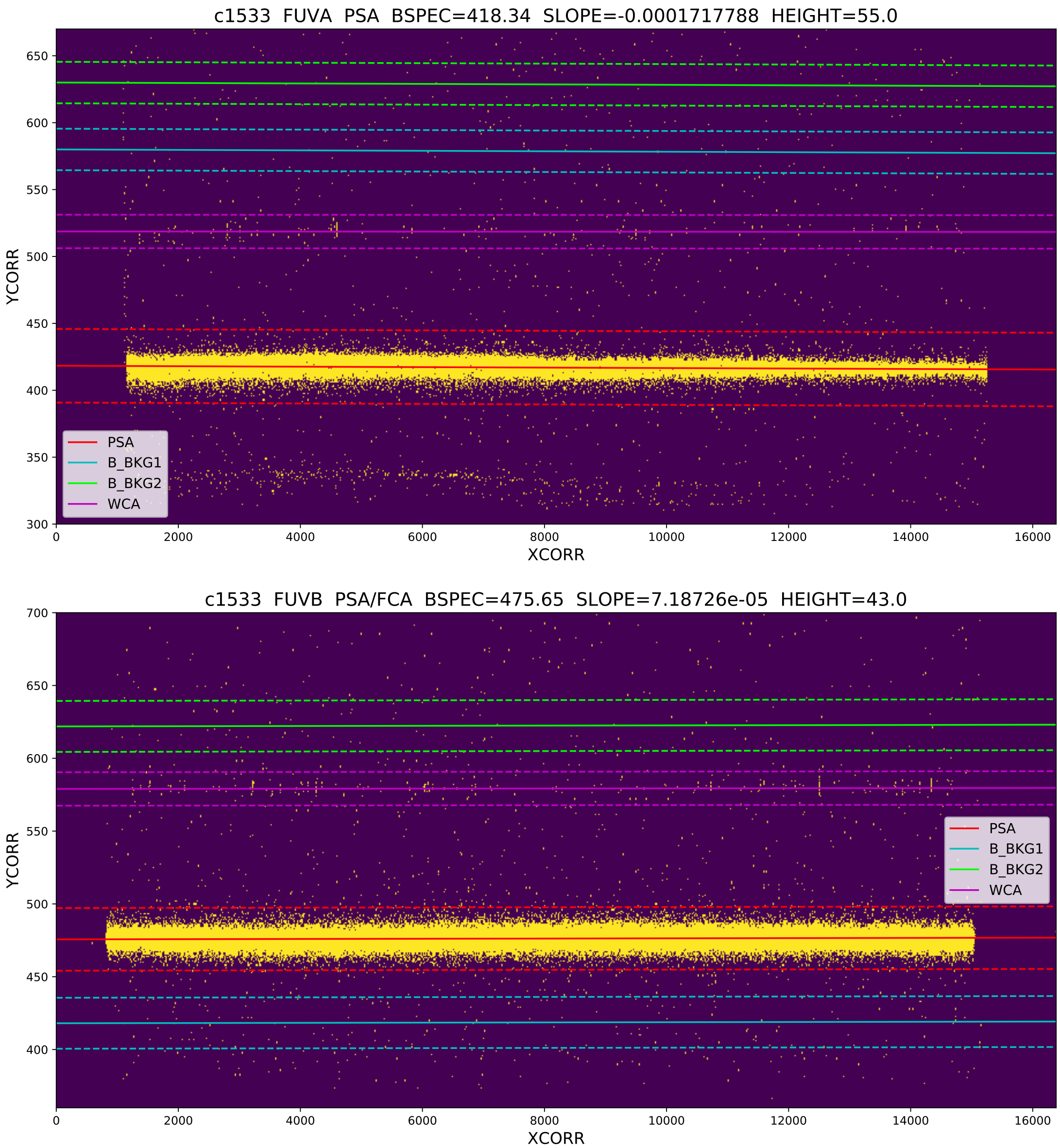

Figure 2. Images of the 2-D spectra of WD 0308–565 FP-POS = 3 FUVA (*top*) and FUVB (*bottom*), showing the PSA (red) and its background regions (green and cyan), along with the WCA (purple), which is described in detail in Section 4.1.2. The solid lines are the centers of each extraction region, and the dashed lines show the upper and lower bounds.

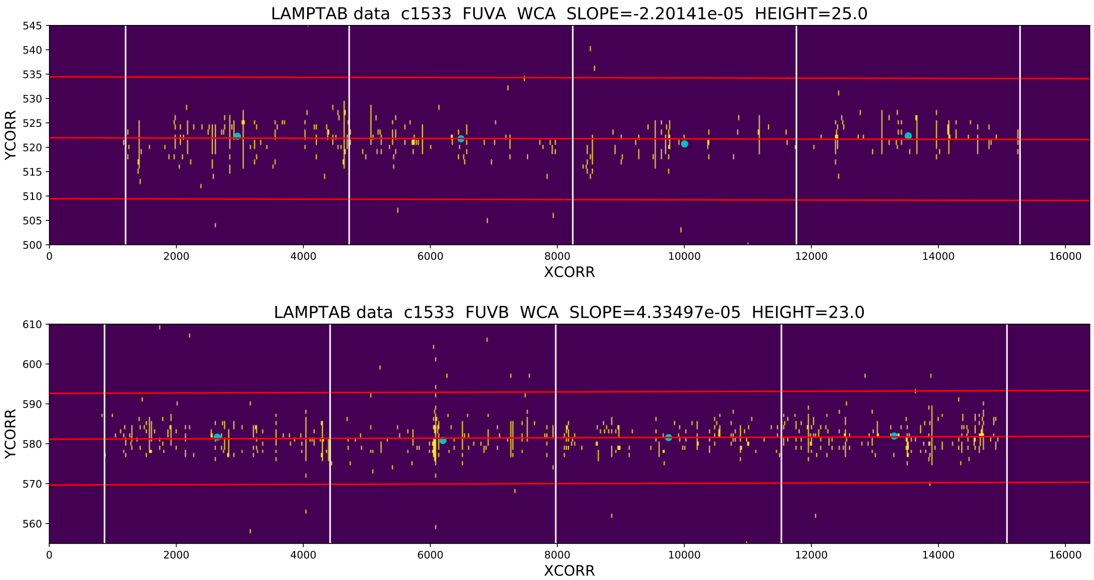

Figure 3. 2-D spectral images showing the high signal-to-noise data from Program 15459, FP-POS = 3, FUVA (*top*) and FUVB (*bottom*), which are used to determine the SLOPE and HEIGHT values for the G160M/1533 WCA XTRACTAB. The symbols and lines are as defined in Figure 1. The final SLOPE and HEIGHT values for both segments are given in the figure titles.

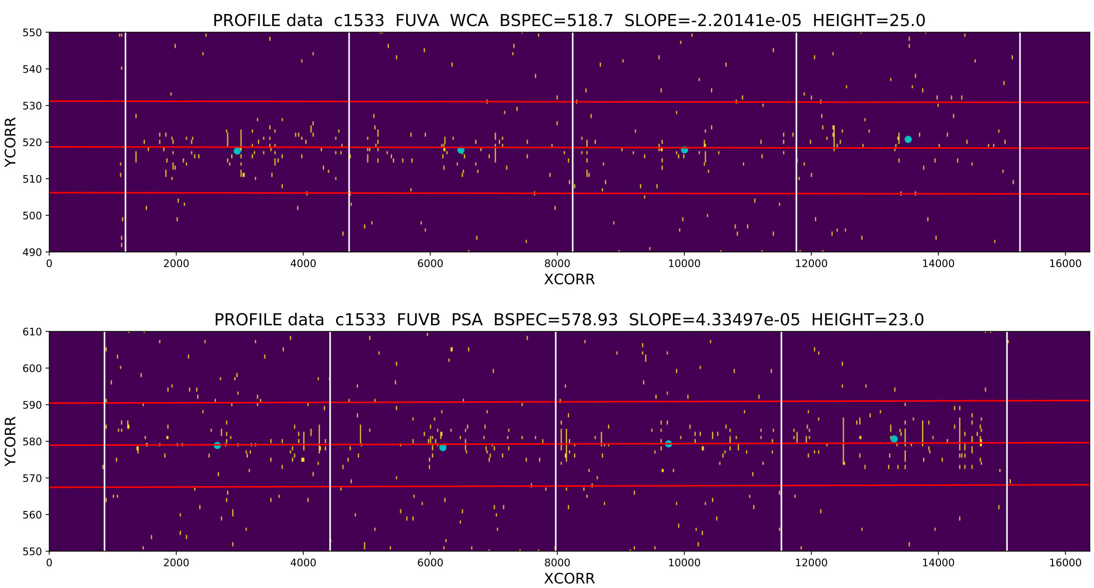

Figure 4. 2-D spectral images showing the WCA data from Program 15458, FP-POS = 3 FUVA (*top*) and FUVB (*bottom*), which are used to determine the final B_SPEC values for the G160M/1533 WCA XTRACTAB. The symbols and lines are as defined in Figure 1. The final SLOPE, HEIGHT, and B_SPEC for both segments are given in the titles.

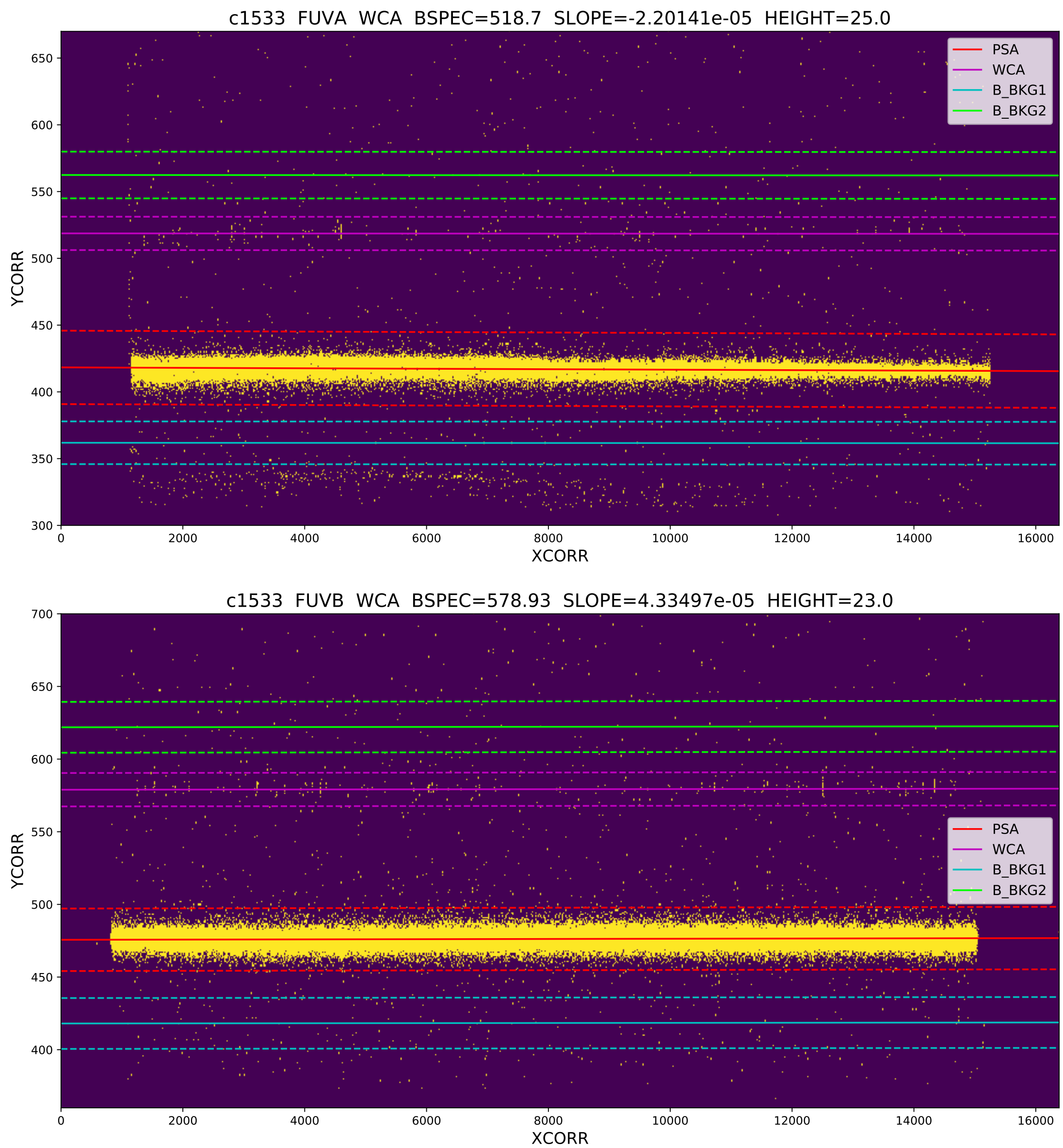

Figure 5. 2-D spectral images of FP-POS = 3 WD 0308–565 FUVA (*top*) and FUVB (*bottom*), showing the WCA (purple) and its background regions (green and cyan), along with the location of the PSA (red). The solid lines are the centers of each extraction region, and the dashed lines show the upper and lower bounds. The background boxes for the WCA are the same as for the G160M/1577 PSA, with the exception that on segment A, the lower background box (B_BKG1) is lowered by five pixels to avoid overlapping with the G160M/1533 PSA extraction box.

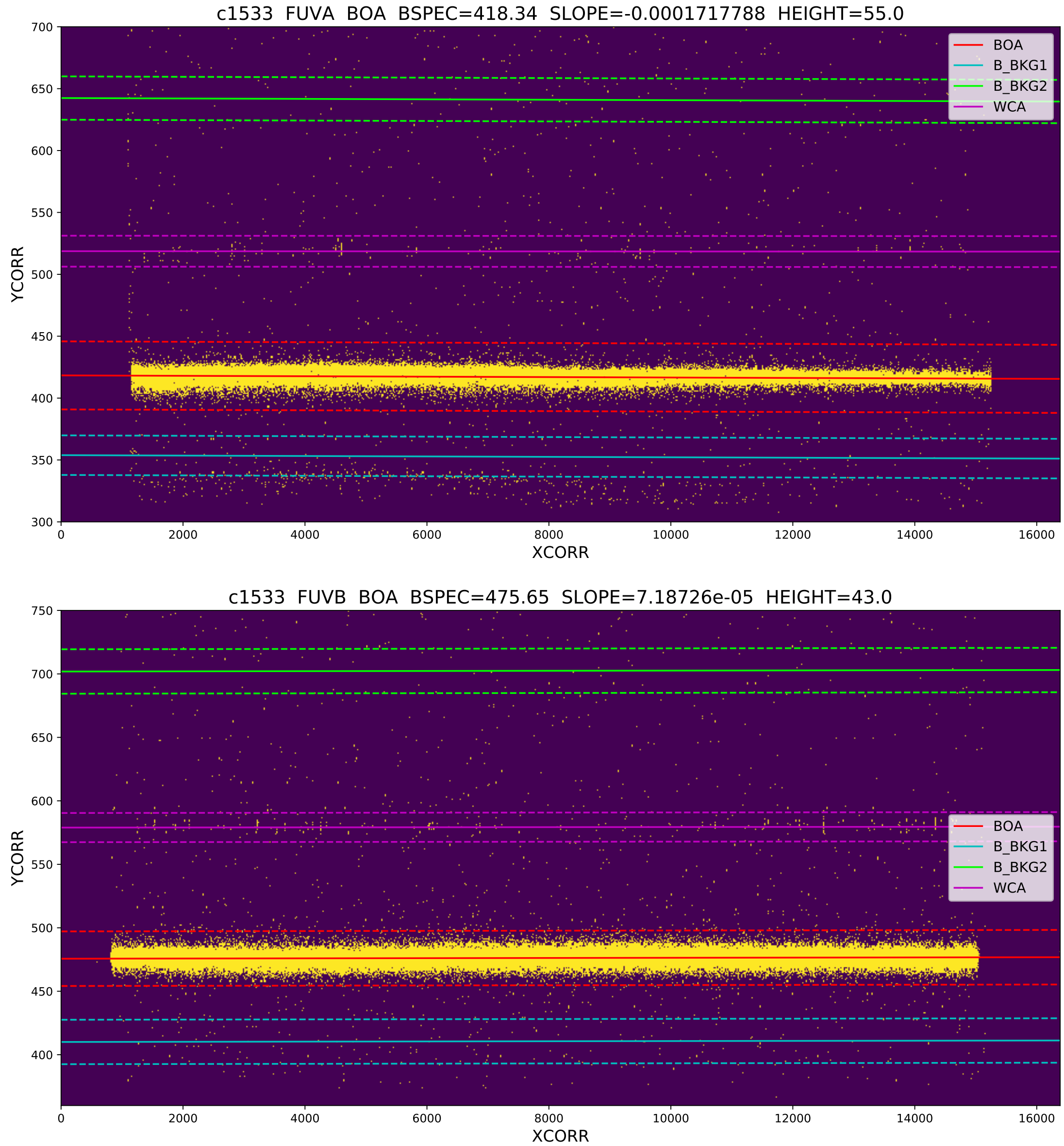

Figure 6. 2-D spectral images of FP-POS = 3 WD 0308–565 FUVA (*top*) and FUVB (*bottom*), showing the BOA (red) and its background regions (green and cyan), along with the location of the WCA (purple). The solid lines are the centers of each extraction region, and the dashed lines show the upper and lower bounds. The background regions for the BOA are offset from the G160M/1577 PSA background region values as follows: on FUVA, the lower background region (B_BKG1) is lowered by 8 pixels and the upper is raised by 100 pixels, and on FUVB, B_BKG1 is lowered by 8 pixels and B_BKG2 is raised by 80 pixels.

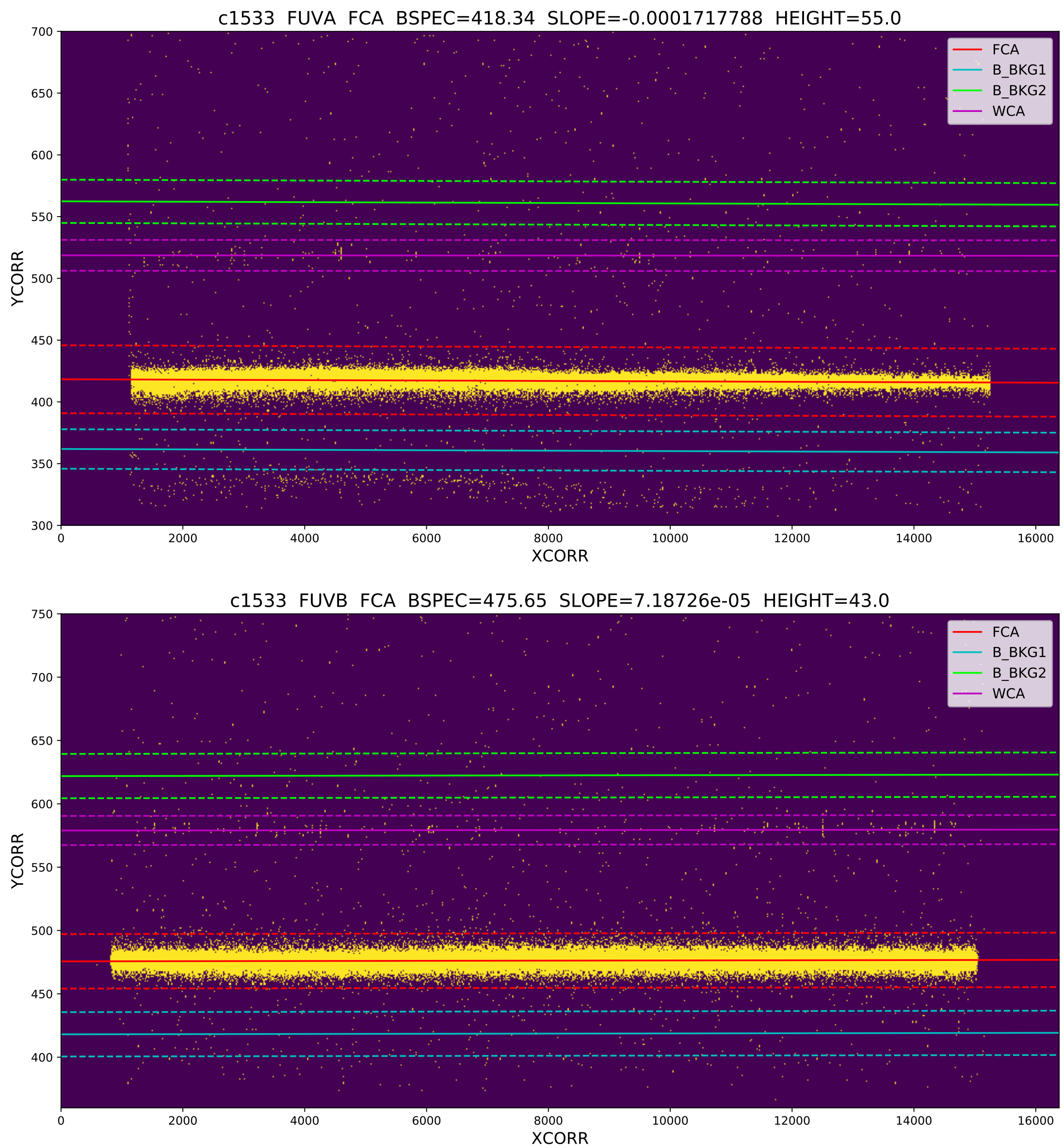

Figure 7. 2-D spectral images of FP-POS = 3 WD 0308–565 FUVA (*top*) and FUVB (*bottom*), showing the FCA (red) and its background regions (green and cyan), along with the location of the WCA (purple). The solid lines are the centers of each extraction region, and the dashed lines show the upper and lower bounds. The background regions for the FCA are the same as those for the G160M/1577 PSA setting.

4.2 Trace Correction Reference File (TRACETAB)

The TRCECORR step in CalCOS corrects for residual detector distortions resulting from imperfect geometric and walk corrections. The spectral trace of a target in the FUV can wander up and down by several pixels over the full wavelength range and needs to be corrected before the TWOZONE extraction occurs. The trace for every observing mode is held in the TRACETAB reference file. The TRACETAB has 8 columns: SEGMENT, OPT_ELEM, CENWAVE, APERTURE, DESCRIP, TRACE_YLOC, TRACE, ERROR. TRACE_YLOC is the location of the center of the trace. TRACE is an array of 16384 floating point numbers where the index is the value of `XCORR` and the value is the offset to be subtracted from each event's `YFULL` value. ERROR is also an array of 16384 floating point numbers that gives the statistical error of the TRACE measurement. Table 3.17 in the COS Data Handbook gives a summary of all the TRACETAB columns. Entries for the PSA and BOA apertures are given in the TRACETAB; we perform this analysis for the PSA only and copy it into the BOA row. Due to this, the use of the BOA is discouraged at LP3 and beyond.

The analysis of the trace for G160M/1533 follows what was done for the other G160M observing modes for the move to LP4 using data from Program (PI M. Rafelski). This work is described in detail in the COS ISR 2018-21 (Rafelski et al. 2019), but a brief description is given here. We start with the calibrated `corrtag` exposures for each FP-POS and segment for the targets WD 0308–565 and GD 71. We first compute individual traces for each of the exposures. A 2-D spectral image is created in `XCORR` and `YCORR` space, and any events with serious data quality flags are removed. For each column in these images, a flux-weighted y-centroid is computed. Each 2-D image is then summed along the dispersion direction to compute a reference flux-weighted y-centroid value. The trace for each exposure is then just the centroids for each column subtracted from the reference center value. Traces with missing data due to bad data quality are interpolated.

Composite traces for each segment are then computed by taking the median of all the traces (one trace per FP-POS exposure) of either segment. The offset needed to align the exposures is then just the median of the composite trace subtracted from the median of the trace for each exposure. This offset is then subtracted from the `YCORR` and `YFULL` arrays of the `corrtag` files so that all of the traces are aligned. Lastly, all events from each FP-POS are then written to a combined `corrtag` file.

To compute the final traces for each segment, we repeat the process of creating 2-D images out of the combined `corrtag` files just created and find the flux-weighted y-centroid of each column. We then compute the reference centroid by collapsing the 2-D image along the dispersion direction and finding the flux-weighted y-centroid. The final TRACE entry for each segment will be the centroids of each column subtracted by the reference centroid. The final step of this process is to remove the final computed trace from the aligned and summed `corrtag` files created above, which are used later for the creation of the profile. Figure 8 shows the final trace for both G160M/1533

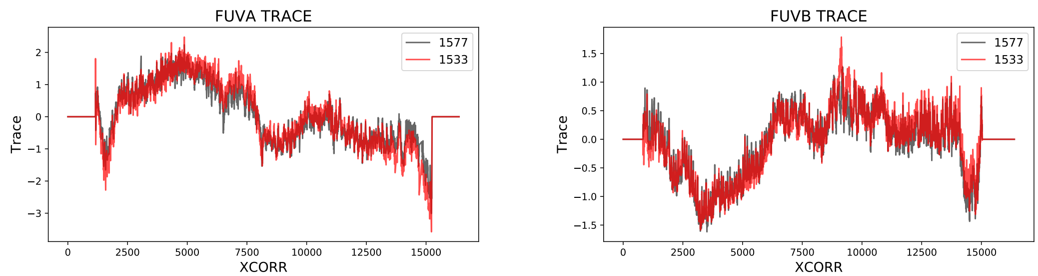

Figure 8. The spectral trace for G160M modes 1533 (in red) and 1577 (in gray), for FUVA (*left*) and FUVB (*right*). The shape of the trace for the two observing settings is very similar.

segments, compared with the traces for the G160M/1577 setting. We find that the traces of both settings are similar in shape.

4.3 Profile Reference File (PROFTAB)

The PROFTAB reference file has 8 columns: SEGMENT, OPT_ELEM, CENWAVE, APERTURE, DESCRIP, CENTER, ROW_0, and PROFILE. The PROFILE contained in this file is trimmed down from the full size of the detector in order to make the reference file a manageable size, so the CENTER and ROW_0 values convert between full-sized detector and profile coordinates. CENTER is the y-location of the flux-centroid of the profile in full-sized (`XFULL`, `YFULL`) array coordinates. ROW_0 is the index of the first row of the profile in the full-sized array. PROFILE is the 2-D array that gives the profile in the cross-dispersion direction for each column of data in `XFULL`, `YFULL` space (offset by ROW_0). The APERTURE column is set to ANY, meaning all apertures will use the same values. Table 3.18 in the COS Data Handbook has a full summary of all the PROFTAB columns.

The ALGNCORR step in CalCOS calculates the flux-weighted y-centroid of science data and compares that to the flux-weighted y-centroid of a reference PROFILE at the same observing setting as the science data. The difference between the two centroids is then applied to the `YFULL` values of the events in the science data, so that the datasets are aligned and the TWOZONE extraction is performed accurately. The profiles are also analyzed to determine the boundaries of INNER and OUTER zones during the X1DCORR step in CalCOS when the XTRACTALG is set to TWOZONE.

As with the trace, the analysis of the G160M/1533 profile follows what was done for the other G160M observing modes for the move to LP4, which is described in detail in the COS ISR 2018-21 (Rafelski et al. 2019). In short, the profiles are created from the same aligned and summed `corrtag` files created for the trace in Section 4.2, meaning the data are already corrected for the shape of the trace. We then create 2-D spectral images in `XFULL` and `YFULL` space. The images for each segment are truncated to a height that we assume includes 100% of the counts from the target. This height is defined by the G160M/1533 rows in the XTRACTAB as follows:

$$\begin{aligned}\text{longest distance} &= \text{larger of (distance between B\_SPEC \& B\_BKG1,}\\ &\quad\ \text{distance between B\_SPEC \& B\_BKG2)}\\ \text{largest height} &= \text{larger of (B\_HGT1, B\_HGT2)}\\ \textbf{height of profile} &= 2 \times \left(\text{longest distance} + \frac{\text{largest height}}{2}\right)\end{aligned}$$

The height of the profile is calculated for each segment, then the larger of the two is adopted for both segments. The truncated height for G160M/1533 is 327 pixels. Once truncated, any pixels that fall outside of the extraction region defined by HEIGHT and B_SPEC in the XTRACTAB are set to a value of zero. However, for the LP4 profile calculations (from COS ISR 2018-21, Rafelski et al. 2019), all of the observing modes are truncated to the height of the largest mode, which is 359 pixels. We therefore had to pad the G160M/1533 profiles with zeros to the height of the other observing modes, so that they could be added into the PROFTAB FITS file correctly. We also add 16 pixels to the ROW_0 column to make up for this extra padding. Then, the left and right sides of the profiles are linearly interpolated. Lastly, each column in the profile is normalized by the summed counts in each column. Figure 9 shows the final profiles for FUVA and FUVB, and the 0.05%, 10%, 90%, and 99.5% enclosed energy contours are marked by the pink lines from bottom to top. The 0.05% and 99.5% contours contain 99% of the profile flux, and the 10% and 90% contours contain 80% of the flux.

4.4 TWOZONE Spectral Extraction Reference File (TWOZXTAB)

The TWOZXTAB reference file contains the starting values for the object center and background regions and the enclosed energy boundary values used in the X1DCORR step of CalCOS when XTRACTALG is set to TWOZONE extraction. The TWOZXTAB has columns SEGMENT, OPT_ELEM, CENWAVE, APERTURE, B_SPEC, B_BKG1, B_BKG2, HEIGHT, BHEIGHT, BWIDTH, LOWER_OUTER, UPPER_OUTER, LOWER_INNER, and UPPER_INNER. Table 3.19 in the COS Data Handbook gives a summary of all the TWOZXTAB columns. B_SPEC is the center of the science extraction aperture, and it is used by the ALGNCORR step to get an initial guess for the location of the spectral trace. B_BKG1 and B_BKG2 are the center of the background regions, HEIGHT is the height of the target extraction region, and BHEIGHT is the height of the background extraction regions. BWIDTH is the width of the smoothing box used to smooth the background region in the extraction step. LOWER_OUTER, UPPER_OUTER, LOWER_INNER, and UPPER_INNER define the fractional flux energy boundaries.

Some parameters of the TWOZXTAB are the same as in the XTRACTAB, including B_BKG1, B_BKG2, and HEIGHT. The B_SPEC value is copied from the CENTER value in the PROFTAB. The BHEIGHT value is the smaller height of the two background regions from the XTRACTAB. The values of LOWER_OUTER,

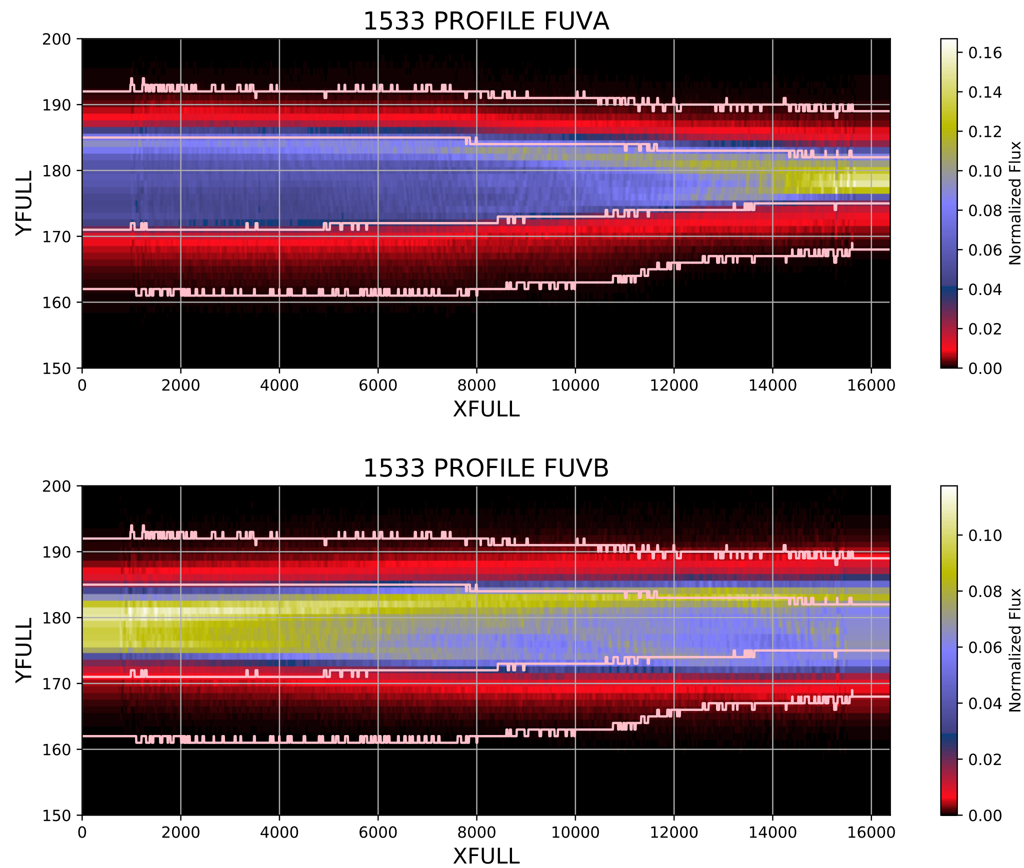

Figure 9. The profile images for G160M/1533 for segments FUVA (*top*) and FUVB (*bottom*). The pink lines show, from bottom to top, where the 0.05%, 10%, 90%, and 99.5% enclosed energy contours lie.

UPPER_OUTER, LOWER_INNER, and UPPER_INNER are unchanged from the G160M/1577 values: 0.5%, 99.5%, 10%, and 90%, respectively. The BWIDTH value is also unchanged from the G160M/1577 value of 100. Only the PSA and BOA are included in the TWOZXTAB, and so the above values are copied for each aperture separately.

5. Scientific Testing

To test the new G160M/1533 PSA and WCA rows of the XTRACTAB, we start by plotting the new BOXCAR extraction regions (determined using WD 0308–565 FP-POS = 3 data) onto 2-D spectral images of WD 0308–565 data taken at FP-POS = 1, 2, and 4 that are created from the `corrtag` files in `XCORR`, `YCORR` space. This is simply a visual inspection to ensure that the G160M/1533 entries for the HEIGHT, SLOPE, and B_SPEC of each aperture are appropriate for all FP-POS settings. These results for FP-POS = 1 are shown in Figure 10. The results look visually reasonable for each FP-POS, and so this test is passed. As a more robust test, we calibrate the FUVA GD 71 data from Program 15458 using the new XTRACTAB file but still using the preliminary versions of the LAMPTAB, DISPTAB, and SPWCSTAB and the calibration switches given in Table 2. With these calibrated `corrtag` files, we create 2-D spectral images in `FULL` space instead of `CORR` like before. We then overplot the new extraction regions on each spectral image. Doing this visual inspection ensures that the derived entries for the G160M/1533 rows are appropriate for other targets and that the conversion from `CORR` to `FULL` coordinates is done correctly. We do this for each FP-POS and show the results for FP-POS = 1 in Figure 11. To test FUVB, we calibrate the G160M/1533 observations of ϵ Eri, which were taken to derive the wavelength calibration for the new mode (Program 15457; PI A. Fox), in the same manner. A visual inspection of the spectral profile and BOXCAR extraction regions for both segments shows that this test is passed as well.

We then test the TWOZONE extraction reference files in a variety of ways. First, to test the trace correction, we recalibrate the Program 15458 data that were used to create the updated TRACETAB, PROFTAB, and TWOZXTAB, this time with XTRACTALG = TWOZONE, ALGNCORR and TRCECORR set to PERFORM, and using the new TRACETAB, PROFTAB, and TWOZONE reference files (along with the G160M/1533 LAMPTAB and DISPTAB). We also run a comparison calibration with XTRACTALG = BOXCAR and ALGNCORR and TRCECORR set to OMIT, using the same reference files previously stated. With the `corrtag` files output from these two calibrations, we can compare the 2-D spectral images created in `FULL` space to see how well the spectral profile is straightened when the trace correction is performed using the new TRACETAB. Figure 12 shows these comparisons for FUVA and FUVB. To confirm that the trace is adequately removed from the spectral image, we calculate the flux-weighted centroid of each column in each image (shown with the red line), and then compute the standard deviation of the centroids (given in each legend). Without the trace correction, the standard deviations of the centroids are 1.10 for FUVA and 0.68 for FUVB. With the trace correction on, the standard deviations are reduced to 0.35 (FUVA) and 0.31 (FUVB). Therefore, the spectral profiles are well straightened by the new TRACETAB, and this test is passed.

We can then compare the `x1d` spectra extracted using the BOXCAR and TWOZONE methods. The BOXCAR extraction box is designed to collect 100% of the flux of a target, while the TWOZONE extraction method is designed to collect flux within a 99% enclosed energy contour. This means there should be less than 1% difference between their output 1-D spectra. Figure 13 shows comparisons of the 1-D spectra of WD 0308–565 FP-POS = 3 FUVB extracted using the two different algorithms. The top panel of the plots shows that the net count rate for each method is very similar, and the bottom panel confirms this, showing that the two spectra agree to within $\sim 1\%$ at most wavelengths. The middle panel shows the difference between the data quality flags using the parameter n, where DQ = 2^n. The BOXCAR extraction

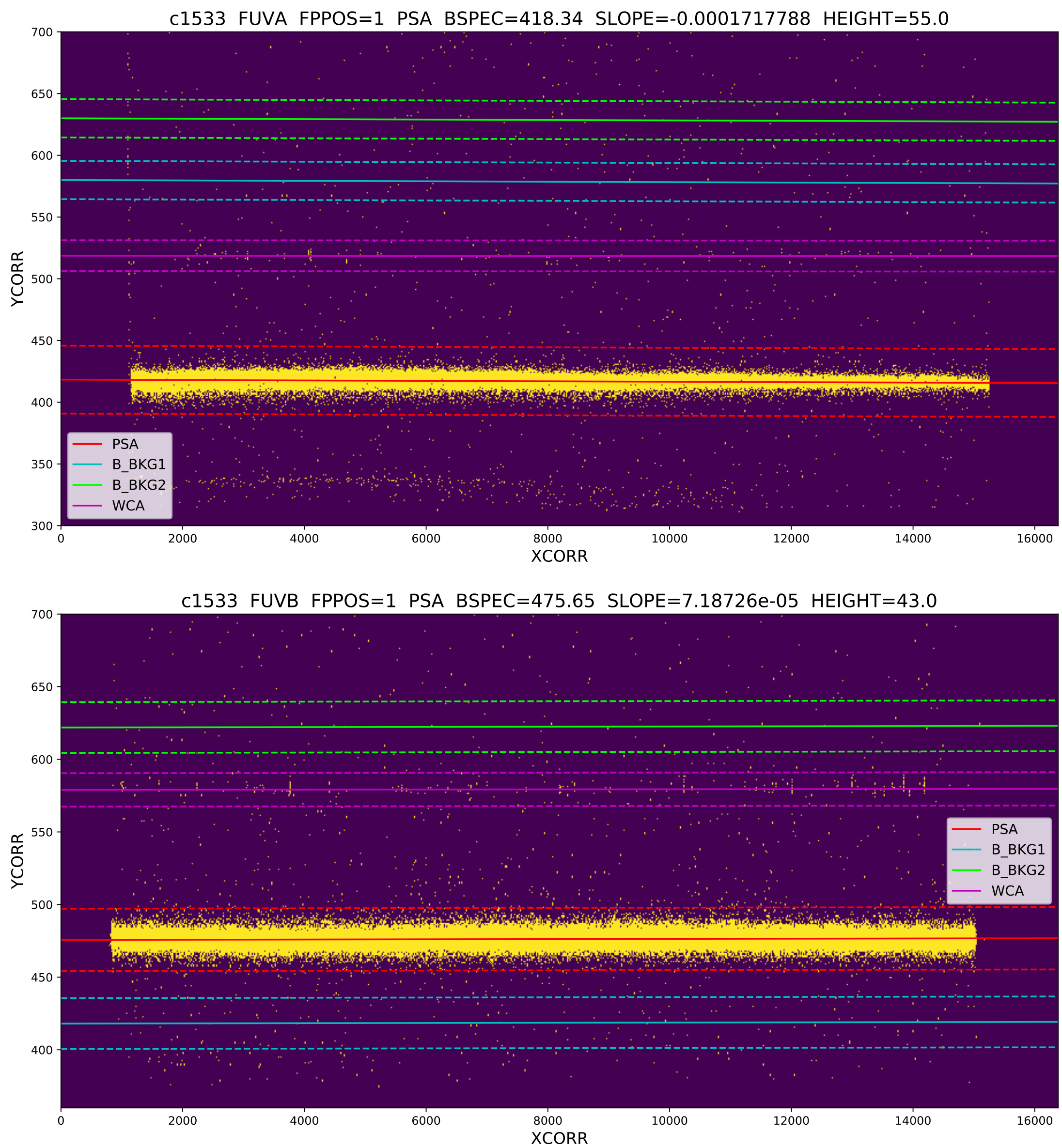

Figure 10. 2-D spectral images of segments FUVA (*top*) and FUVB (*bottom*) of FP-POS = 1 WD 0308–565 data with the PSA (red), WCA (purple), and the PSA background regions (green and cyan) overplotted.

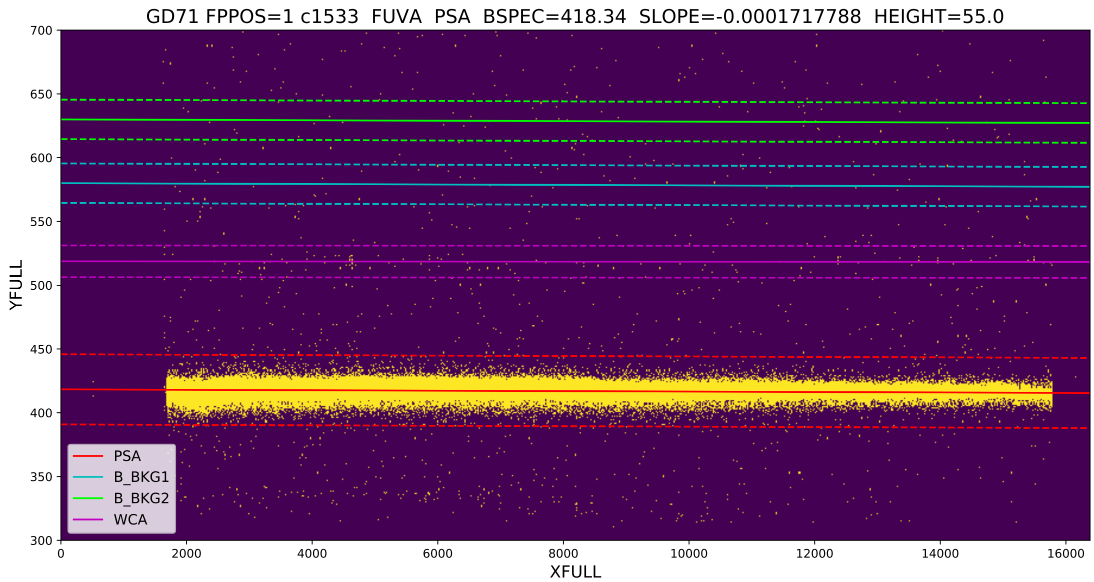

Figure 11. 2-D spectral image of segment FUVA of FP-POS = 1 GD 71 data with the PSA (red), WCA (purple), and the PSA background regions (green and cyan) overplotted. These data were calibrated with CalCOS using the newly updated XTRACTAB and are plotted in `FULL` space to ensure that the conversion from `CORR` to `FULL` space is done correctly with the new reference file.

method removes any serious data quality flags, while the TWOZONE method will only remove them if they are in the inner 80% of the profile. We see two areas with $n = 10$ (low response region) and one area with $n = 13$ (gain sag) that have been flagged in the BOXCAR extraction, but not in the TWOZONE extraction. Though we only show the results for WD 0308–565 FP-POS = 3 FUVB data, this test was performed on both segments and all FP-POS, as well as on the GD 71 data, and each passed.

Finally, we check that the enclosed energy contours that are computed by CalCOS as a part of the TWOZONE extraction method are similar to contours that are manually computed from the 2-D spectral image created from `corrtag` files in `full` space. We perform this test on FUVA GD 71 FP-POS = 3 and FUVB WD 0308–565 FP-POS = 3 data. The results are shown in Figure 14 for both segments. We plot the 80% and 99% extraction contours output by CalCOS in the `x1d` files in red and cyan, respectively. The direct measurements of the 80% and 99% energy contours are found using a cumulative sum in each column and are plotted in green and blue. The manually-computed and CalCOS-computed contours are indeed very similar.

6. Summary

With the testing complete, the XTRACTAB, TRACETAB, PROFTAB, and TWOZXTAB reference files with the new entries for G160M/1533 were merged with

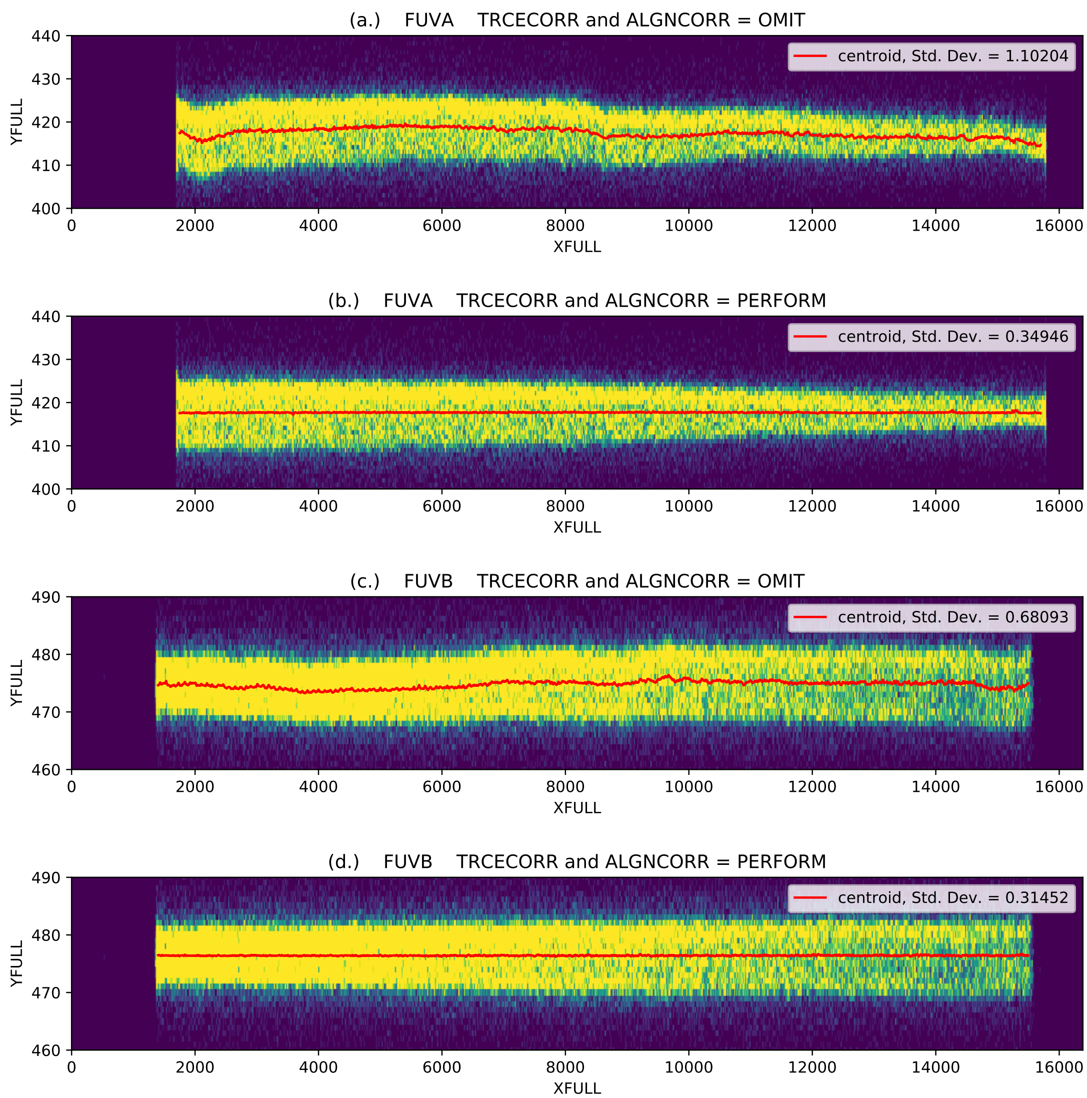

Figure 12. 2-D spectral images of WD 0308–565 FUVA with BOXCAR (*a.*) and TWOZONE (*b.*) extraction and FUVB with BOXCAR (*c.*) and TWOZONE (*d.*) extraction. The red line in each plot traces the flux-weighted centroid calculated for each column in the image, and the standard deviations of the centroids are listed in the legends. The standard deviation measurements are reduced to less than half a pixel for both segments when the trace correction is performed using the TWOZONE extraction algorithm.

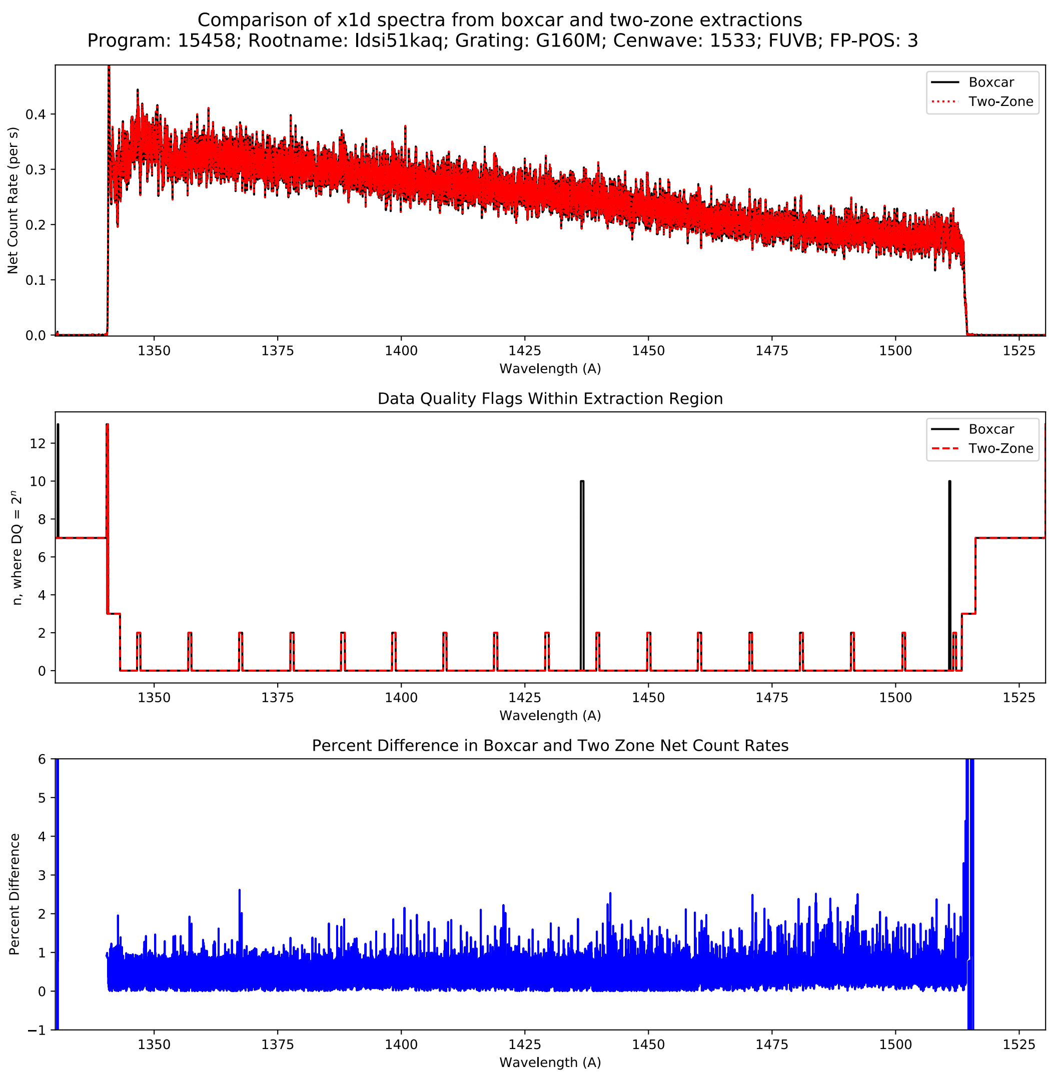

Figure 13. *Top:* Comparison of 1-D WD 0308–565 FP-POS = 3 FUVB spectra extracted using the BOXCAR and TWOZONE extraction algorithms. *Middle:* Difference between the data quality flags plotted using the parameter n, where DQ = 2^n. *Bottom:* Percent difference between the net count rate calculated with the TWOZONE extraction algorithm and the net count rate calculated with the BOXCAR extraction algorithm.

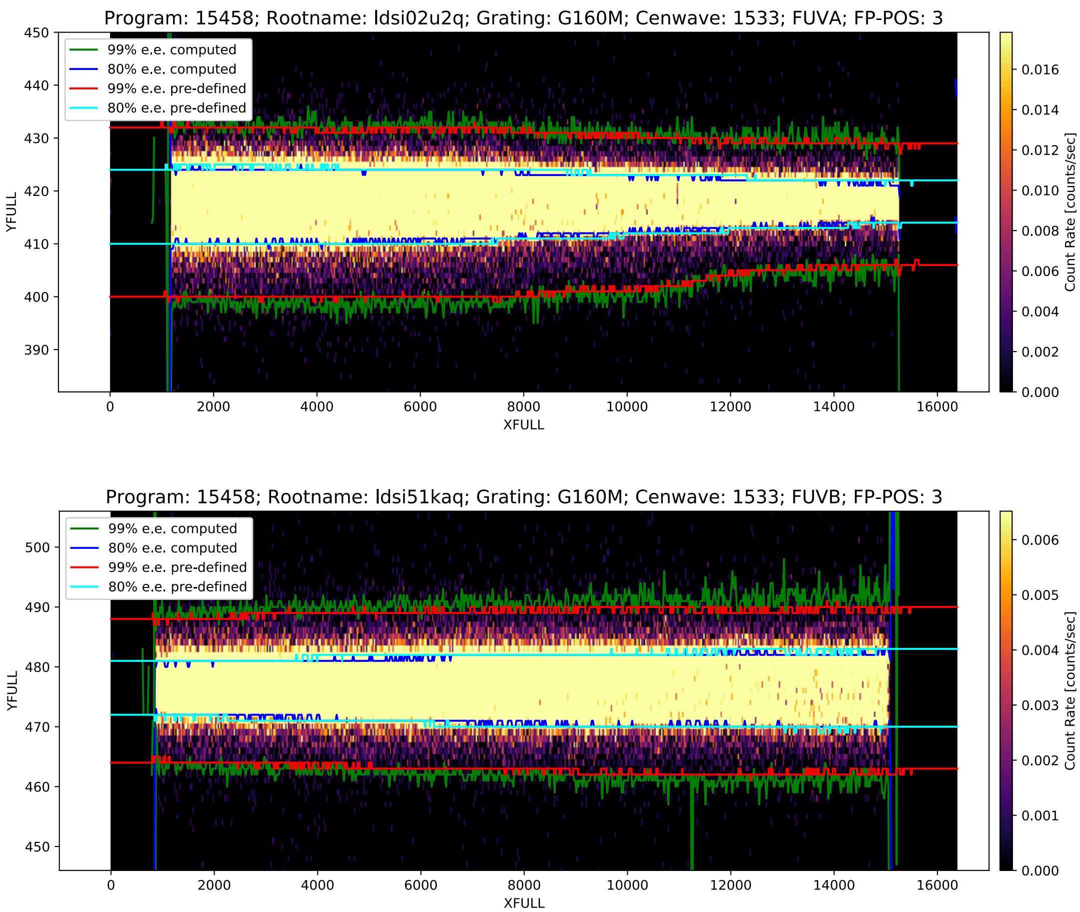

Figure 14. `flt` images of GD 71 FP-POS = 3 FUVA (*top*) and WD 0308–565 FP-POS = 3 FUVB (*bottom*) showing the comparison of the enclosed energy contours calculated via CalCOS (in red and cyan) and those calculated manually (in green and blue). The contours from both methods closely align with each other, which validates the values in the new TRACETAB, PROFTAB, and TWOZXTAB reference files.

Table 3. Final G160M/1533 Values for Key Columns in the XTRACTAB, TRACETAB, PROFTAB, and TWOZXTAB Reference Files[1]

File	Column	FUVA	FUVB
XTRACTAB	SLOPE	–0.000172	7.187×10^{-5}
	B_SPEC	418.34	475.65
	HEIGHT	55	43
TRACETAB	TRACE_YLOC	418.69	477.4
PROFTAB	CENTER	418.77	477.19
	ROW_0	239	298
TWOZXTAB	B_SPEC	418.77	477.19
	HEIGHT	55	43
	BHEIGHT	31	35

[1]All values listed are for the PSA.

the new entries for the G140L/800 setting. The files were then retested to ensure no mistakes had been made during the merging process. The final files *2bj2256il_1dx.fits*, *2bj2256jl_trace.fits*, *2bj2256ql_profile.fits*, and *2bj2256nl_2zx.fits* were delivered to the HST Calibration Reference Data System (CRDS, https://hst-crds.stsci.edu) in 2018 November. The key values in each reference file for the new G160M/1533 mode are summarized in Table 3.

Acknowledgments

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Version 1: 13 May 2019 – Original Document

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