ABSTRACT

The wavelength dispersion coefficients and zero points of the COS FUV G130M and G160M gratings at each lifetime position (LP1, LP2, LP3, LP4) have been re-derived. In this document we present the analysis behind the improvements of the wavelength solutions for data obtained at LP2 (i.e., between July 23, 2012 and February 9, 2015) for all central wavelengths except G130M 1055, 1096, and 1222. The investigation was similar to that performed for LP1 (Plesha et al. 2018). Archival data of objects observed with both COS and overlapping STIS echelle modes were used to determine the dispersion coefficient and an initial measurement of the zero point for each cenwave setting. However, the number of targets was smaller than for LP1 and not all cenwave modes had enough data to derive a solution. An analysis of ray-trace models found that the apparent variation of dispersion with central wavelength is mainly due to linear focus offsets applied to maintain resolution for each cenwave setting. Thus, to fill in the missing cenwaves and improve the statistical results, LP2 dispersion terms were combined with those from LP1 and were fit with ray-trace models as a function of Optics Select Mechanism 1 (OSM1) focus position. Zero points then were refined with archival COS data where multiple cenwaves were used in the same visit, which provided a better relative alignment between COS modes. The wavelength solution accuracy has been improved from $\sim 15 \text{ km s}^{-1}$ (6 pixels) to $\sim 7.5 \text{ km s}^{-1}$ (3 pixels).
1. Introduction

Due to the effects of gain sag, spectra obtained with the COS FUV detector were repositioned to a new cross-dispersion location, lifetime position LP2, for normal operations on July 23, 2012. Osten et al. (2013) summarize the extensive program to recalibrate the instrument after the move. As part of this effort, Sonnentrucker et al. (2013) checked the wavelength calibration and concluded that the wavelength solutions for the G130M, G160M, and G140L gratings did not need to be modified from those for the original spectrum location, LP1, derived during Servicing Mission Orbital Verification (SMOV) after the installation of COS into HST (Oliveira et al. 2010). Their analysis was based on observations taken at the extreme cemwaves for the M gratings (1291 and 1327 for G130M; 1577 and 1623 for G160M) and cemwave 1105 for G140L. Subsequently, Plesha et al. (2018) undertook an effort to improve the LP1 wavelength calibration for G130M and G160M to achieve co-alignment of all the standard mode cemwaves to half a resolution element (± 3 pixels). This study did not use new observations, but rather took advantage of the fact that numerous targets observed with the STIS echelle gratings were re-observed with COS. The previous accuracies of the COS wavelength scales at LP1, ~ 15 km s⁻¹, were improved to ~ 7.5 km s⁻¹ by tying them to the higher-accuracy calibration for the STIS echelle modes (~ 2 km s⁻¹). In this report, we discuss the continuation of this effort for
observations taken at LP2.

The wavelength solutions for each segment (i.e., FUVA and FUVB) on COS can be found in the dispersion reference file (DISPTAB) and are defined using the equation

$$\lambda = a_0 + a_1 \times x_{\text{prime}} + a_2 \times x_{\text{prime}}^2,$$

where $x_{\text{prime}}$ is calculated from XFULL pixel coordinates (thermally, geometrically, drift and FP-POS corrected) and zero-point offsets between those derived on-orbit during SMOV ($d$) and those derived in thermal vacuum (TV) testing in 2003 ($d_{TV03}$):

$$x_{\text{prime}} = XFULL + d_{TV03} - d$$

(Oliveira et al. 2010). For the FUV channel, the medium-resolution grating wavelength solutions are linear ($a_2 = 0$). In addition, since the new calibrations are based solely on external targets and are not referenced to the wavelength solutions derived from TV03 data, the zero-point offsets to TV03 are not needed and $d = d_{TV03} = 0$, so $x_{\text{prime}} = XFULL$. As with LP1, we updated both $a_0$ and $a_1$ for the G130M and G160M standard modes using a cross-correlation technique, mapping COS data to STIS wavelengths of the same target, to derive initial zero points and dispersion coefficients. The dispersion coefficients were fit to ray-trace models, and the zero points were adjusted by performing cross-correlations between COS exposures of the same target taken at a different grating setting in the same visit, i.e., with the same target centering. With this effort, we aimed to increase the FUV wavelength accuracy to $\sim 7.5$ km s$^{-1}$, i.e., from one COS resolution element (6 pixels) to half a resolution element (3 pixels).

On November 11, 2016 the DISPTAB, 0bn1606sl_disp.fits, was released for use at LP2. The details of the selection of our data used for both the COS-to-STIS correlations and the COS-to-COS correlations are outlined in Section 2. The methodology used at LP2 compared to LP1 is discussed in Section 3. The results of our analysis are presented in Section 4, the details of the reference file, in Section 5 and conclusions, in Section 6. Appendix A discusses the effect of grating focus position on dispersion and the TV03 wavelength solutions. Appendix B presents statistics on the relative alignments now achieved between cenwaves.

2. Data Selection

To derive the new wavelength solutions, the HST archive was mined for targets observed both by COS (G130M, G160M) at LP2 and STIS (E140H, E140M, E230M), just as was done for the LP1 analysis. Targets were selected based on their spectra having a good sampling of unblended lines, exhibiting relatively flat local continua at the features to be measured, and possessing exposure levels of sufficient S/N for cross-correlation. There were three unique targets observed with G130M only and five unique targets that used both G130M and G160M. This was much fewer than that on hand for LP1, where 16 targets were available for each of the two gratings. We took special care to exclude
visits of programs or entire programs where COS was operating in a non-standard way. The distribution of the targets and modes used are shown in Figure 1, while the specific association names are outlined in Table 1.

To update zero points and test the updated wavelength solutions, we again mined the HST archive for COS exposures at LP2 where targets had been observed at multiple grating settings within an observation visit, especially where various cenwaves were used. This selection method helps to improve the co-alignment of spectra, since any offsets due to a target-centering error are eliminated for exposures in the same visit. The distribution of the number of exposures we used with the different cenwave settings is shown in Figures 2 and 3. In total, there were 52 unique targets with G130M data and 64 unique targets with G160M data used for the COS-to-COS testing, compared to 95 and 87 respectively for LP1.

Like at LP1, we rejected specific windows where the spectral feature was too weak (S/N \( \sim 5 \)) in a particular exposure, but we continued to use them in other exposures when they had a high enough S/N. For the COS-to-STIS correlations, these rejections are listed in Table 2a, and for the COS-to-COS correlations, Table 2b. As before, we used the x1d files, which are the product for each individual FP-POS exposure and retain data where a bad DQ flag may fall in the spectrum, not the combined x1dsum files.

At LP2, unlike LP1, not every cenwave had sufficient data across the entire detector to compare to STIS. Thus, there are several cenwaves where the targets did not contain enough features to determine a reliable linear wavelength solution (1327/FUV A, 1589/FUV A, 1600/FUV A, 1623/FUV A). In these instances we needed a different approach for the calibration, which is discussed in more detail in Section 3. The same issue of insufficient data occurred for the COS-to-COS testing, which resulted in no comparisons of the 1300 vs. 1318, 1327 vs. 1300, and 1327 vs. 1318 pairs for both FUV A and FUVB segments. Other cenwave combinations had a limited number of windows to perform a cross-correlation, but even with the limited data, we were able to adjust the zero points for all settings to be within the new \( \pm 3 \) pixel goal.
Figure 1. Number of COS exposures sorted by cenwave, FP-POS, and target for both G130M (left) and G160M (right) used to derive the LP2 wavelength solutions by performing cross-correlations to STIS echelle data.
Figure 2. Number of COS exposures sorted by cenwave, FP-POS, and target for G130M used to refine and test the updated LP2 wavelength solutions.
**Figure 3.** Number of COS exposures sorted by cenwave, FP-POS, and target for G160M used to refine and test the updated LP2 wavelength solutions.
### Table 1. Gratings and Rootnames for the COS-to-STIS Cross-Correlations at LP2

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</tr>
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<td>Mrk 509</td>
<td>G130M</td>
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<td>lck102020, lck102010</td>
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### Table 2. Rootnames and Wavelength Ranges of Windows Not Used in Cross-Correlations Due to Low S/N

(a) COS-to-STIS Manual Rejections

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<th>Association Rootname</th>
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<th>Grating</th>
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</table>

(b) COS-to-COS Manual Rejections

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<th>Target</th>
<th>Grating</th>
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</thead>
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<td>Q 1354+195</td>
<td>G130M</td>
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<td>1669.7–1671.7</td>
<td>Q 1354+195</td>
<td>G130M</td>
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</table>
3. Methodology

As described in Plesha et al. (2018), the wavelength calibration procedure using archival data entails multiple iterative steps.

1. After the COS-to-STIS datasets are identified, the STIS echelle data are resampled and convolved to the COS resolution with model line spread functions for each cenwave. Windows surrounding usable features are defined, centroids of the windows are computed in XFULL pixel space, and cross-correlations of the COS and convolved STIS spectra are performed using the old DISPTAB to map them to STIS wavelengths. The COS wavelengths are corrected and converted to the geocentric velocity frame of the exposures, and wavelength solutions are calculated for each segment and cenwave by a linear fit of wavelengths to XFULL values. The measured dispersion terms are then fit through $\chi^2$ minimization to ray-trace models of the relation between dispersion coefficients and cenwave settings. An intermediate DISPTAB is created with the ray-trace dispersion coefficients and measured zero points.

2. The COS-to-COS datasets are processed by CalCOS with the intermediate DISPTAB. The windows for each combination of available spectra during a target visit are aligned by performing a cross-correlation. The resultant shifts, which are largely due to residual zero-point errors in the intermediate calibrations, are aggregated by cenwave pair. The means of the distribution of residuals are then used to adjust the zero points in the DISPTAB.

3. A new DISPTAB is created and the COS-to-STIS and COS-to-COS datasets are reprocessed by CalCOS with it. Cross-correlations are performed with the spectra as before, and the shifts are analyzed to determine if further adjustments are required to keep the residuals to ±3 pixels or to eliminate systematic trends. Issues were usually resolved by finding and excluding problem exposures or windows, then iterating the relevant procedure steps with a revised DISPTAB.

Initial dispersion coefficients from the LP2 COS-to-STIS analysis are shown in Figure 4 along with the ray-trace values delivered for LP1 (Plesha et al. 2018) and, for completeness, those from thermal vacuum ground testing in 2003 (TV03), which were used in the DISPTAB from SMOV. These results indicated that some modes at LP2 would be more difficult to calibrate than at LP1. For segment FUVB, the dispersion coefficients displayed a similar trend with cenwave as LP1, but the measurements were offset for G160M. LP2 ray-trace models had indicated there should be no inherent offset compared to LP1 in simply relocating the spectra to the new cross-dispersion position. Segment FUVA presented additional issues. For G130M, the dispersion coefficients of the extreme cenwaves were inconsistent with the others even though most were well-determined. For G160M, only two cenwaves had sufficient data for meaningful wavelength solutions, and the linear coefficients were offset even further from LP1 than for segment FUVB. Our effort to resolve these problems is discussed in Sections 3.1, 3.2, and 3.3 below.
3.1 Dependence of Dispersion on OSM1 Focus Step

By far, the FUVA segment posed the greatest challenge to the LP2 wavelength calibration because of the missing cenwaves for G160M and the outlying coefficients for G130M. Since final dispersion coefficients are determined by fitting ray-trace models of dispersions vs. cenwave to the measurements, in theory those for missing or deviant cenwaves can be inferred from fits to the others available. For G130M FUVA, it was difficult to decide which coefficients were dependable enough for a ray-trace fit. For G160M FUVA, with only two cenwaves available and the fact that values for the extreme cenwaves in G130M FUVA were incompatible with the interior ones, there was little confidence that a direct fit of the available G160M FUVA data to the models would yield valid estimates for the missing cenwaves. The constant terms in the dispersion equations were even more problematic since the ray-trace zero points had been found to be unrealistic in the LP1 analysis and could not be used.

To determine how we could better use the ray-trace models with these restrictions on FUVA, a review of the underlying cause of dispersion change with Optics Select Mechanism 1 (OSM1) configuration was undertaken to understand the observed
dispersion behavior with cenwave (see Appendix A). For each cenwave, OSM1, which holds the gratings, is rotated to place the spectrum of the appropriate wavelength range on the detector and is translated in focus to achieve the best spectral resolution. Since the FUV channel is essentially a Rowland circle spectrograph, a focus motion also moves the grating closer or farther from the detector, changing the dispersion. As discussed in Appendix A, most of the observed FUV dispersion variation with cenwave is due to the change of focus, with a small component due to the OSM1 rotation.

For the G130M and G160M standard modes, the OSM1 is translated by +170 steps between each increasing cenwave, with all FP-POS exposures for a cenwave taken at the same focus. During spectrograph optimization at LP2, the nominal focus for G130M was changed by +120 steps relative to LP1, and for G160M, +160 steps (Oliveira et al. 2013). Thus, one would expect the LP2 dispersion to change appropriately. For G160M, the dispersion at one cenwave should be about the same as the next higher cenwave for LP1, e.g., LP2 1577 should be about the same as LP1 1589 since each is +160 or +170 steps from LP1 1577. The G130M dispersion changes were expected to be a little less. Basically, the LP2 to LP1 offsets apparent in Figure 4 are not vertical but are horizontal.

In Figure 5 we show both the LP1 and LP2 dispersion measurements vs. OSM1 focus position. Within the errors, for segment FUVB both lifetime positions can be characterized by a single relation for each grating. The same is true for G130M FUV A, except again for the extreme cenwaves. The G160M FUV A LP2 values do not match those for LP1 and required further investigation. The supposition was that if a common LP1/LP2 relation could be determined for this grating/segment mode, then dispersion coefficients for the missing cenwaves could be interpolated from it.

### 3.2 Gain Sag Effects

As part of the investigation into the dispersion problem for segment FUVA, we examined the dependence of residual errors from the COS-to-STIS wavelength solutions with location on the segment. Figure 6 shows the residuals for G130M and G160M in XCORR space, i.e., the physical location of pixels after thermal and geometric correction. Both gratings show a similar anomalous rise at the left side of the panels, suggesting a common cause with the detector segment itself. Most of the data in this region came from exposures of the chromospherically active star ε Eri made just before the switch to lifetime position 3. Thus, suspicions arose that this artifact could be due to walk effects caused by non-uniform gain sag.

Gain sag is caused by charge depletion of the segments with usage and leads to loss of throughput and positional errors in photon locations (Sahnow et al. 2011; Osten et al. 2013). The positional effect, known as walk, increases towards the edges of the segments. The gain can be increased up to a certain level by raising the segment high voltage (HV), but heavily exposed regions will always have a lower gain compared to other places. In the lower panel of Figure 6 we show the modal gain for FUVA measured at the G130M spectrum location at three different times: at the beginning of the LP2
Figure 5. Initial COS-to-STIS dispersion values at LP2 (red circles) compared to the LP1 measurements (black circles) as a function of OSM1 focus position.

era; just before the HV was increased on November 3, 2014; and just after the $\epsilon$ Eri observation near the end of LP2. Besides the overall change in level, the gain for pixels with XCORR less than $\sim 3400$ becomes flatter with time than elsewhere, and localized depressions occur due to the impact of geocoronal Ly $\alpha$ emission at the four FP-POS locations for G140L cenwave 1105. This area corresponds to the hump in residuals for G130M and G160M. The region where the spectrum of G140L/1105 lies on FUVA (centrally located at $Y = 539$) overlaps both G130M ($Y = 528$) and G160M ($Y = 519$), so observations with that mode affect the gain at the M gratings. The artifact for G160M is slightly smaller than G130M apparently because the spectrum is located further away in $Y$ from G140L. Below XCORR $\sim 2000$, errors in the geometric distortion correction cause a sharp turnover in the residuals.

Since this area occurs near the edge of the segment, it has sufficient leverage to bias the dispersion coefficients by providing a tilt to the wavelength vs. XFULL relations. The size of the effect depends on the distribution of measurements across the segment, with G130M/1327 being most affected since there are no windows with XCORR $> 5700$. Thus, for the FUVA wavelength calibrations we ignored the cross-correlation measurements for XCORR $\leq 3400$. When an improved walk correction
along the dispersion direction becomes available to remove the effects of gain sag, this region should be re-examined to determine if these data could then be used in a new wavelength solution.

Figure 6. FUVA residual errors from the final wavelength solution for G130M (top panel) and G160M (middle panel). The bottom panel shows the FUVA modal gain for G130M during the LP2 period: at the beginning (black), prior to the high voltage increase (red), and near the end (blue). The vertical dashed line marks the lower limit of pixel locations used in the final FUVA wavelength solution derivations.

3.3 Determination of LP2 Wavelength Solutions

Since the dispersion coefficients for LP1 and LP2 seemed to follow the same relation with OSM1 focus, and several FUVA cenwaves had insufficient data for wavelength calibration, for LP2 we opted to combine the LP1 and LP2 measured coefficients and perform a $\chi^2$ minimization fit of ray-trace models as was done by Plesha et al. (2018), except the fits were performed as a function of OSM1 focus position rather than cenwave. LP1 results needed to be incorporated for G160M FUVA to obtain dispersion coefficients for the missing LP2 cenwaves, so to be consistent we followed the same procedure for the other modes. Figure 7 illustrates the results. Both LP1 and LP2 now follow the same relation for each grating/segment configuration.
elimination of pixels with $\text{XCORR} \leq 3400$ for FUVA solved the problem with the discordant dispersion values, although G130M/1327 FUVA no longer had adequate data across the segment to compute a solution.

Figure 7. Final LP2 dispersion coefficients (red dashed lines) from combined LP1 and LP2 measurements.

For the zero-point coefficients, we followed the same process as for LP1. A DISPTAB was created with the new ray-trace dispersion coefficients and the LP2 COS-to-STIS constant terms; the COS-to-COS datasets were reprocessed by CalCOS and cross-correlations were performed; and the relative mean offsets between cenwave pairs were used to adjust the zero points. Complications to this were again due to the missing cenwaves for FUVA. Unlike for the dispersion terms, ray-trace models were not found to be usable for the zero points. We did find, however, that the available LP2 values were close to the final LP1 calibration. In Figure 8, we show the LP2–LP1 differences in pixels with the average for each grating/segment mode. Although each grating has a different mean offset for the two segments, the cenwaves within each mode agree to $\pm 1.2$ pixels ($1\sigma$). For the missing cenwaves, then, we added the average LP2–LP1 offset to the corresponding LP1 values and reprocessed the datasets. In a final step, we found that the COS-to-STIS G160M FUVA calibration needed one more correction. The COS-to-COS adjustments for G160M are normalized at cenwave 1600. For FUVA,
since we do not have an initial measurement from COS-to-STIS for 1600, we instead adjusted all the zero points to be normalized to the two available cenwaves, 1577 and 1611. The effect was a small but observable offset of 0.9 pixels to the final zero points.

**Figure 8.** Difference in zero points between the COS-to-STIS LP2 measurements and the final LP1 wavelength solutions (Plesha et al. 2018). Dashed lines are the average values.

### 4. Results

A new dispersion reference file (DISPTAB), 0bn1606sl_disp.fits, was released on November 11, 2016 for use with data taken at LP2. The updated coefficients are summarized in Table 3, rounded off to the significance required to assign a wavelength to a fraction of a pixel. Any data obtained between July 23, 2012 and February 9, 2015 with G130M or G160M standard modes (cenwaves 1291, 1300, 1309, 1318, 1327, 1577, 1589, 1600, 1611, 1623) now use this DISPTAB. The uncertainty in the COS wavelength solutions with the previous DISPTAB derived during SMOV was typically ±15 km s\(^{-1}\). As seen in Figure 9 for the G130M and G160M standard modes we were able to improve this uncertainty to ±7.5 km s\(^{-1}\) (3 pixels exclusive of errors due to target centering). The individual results from the COS-to-STIS correlations are discussed in Section 4.1 while results with the adjusted zero points from the COS-to-COS correlations are discussed in Section 4.2.
Table 3. Rounded, Updated Zero Points \((a_0)\) and Dispersion Coefficients \((a_1)\) for LP2 Modes\(^1\)

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<th>Grating</th>
<th>Cenwave</th>
<th>Segment</th>
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\(^1\)Exact values should be obtained from the DISPTAB.

Figure 9. Residual velocity errors in the new LP2 wavelength solutions for all cenwaves vs. XCORR position. Dashed lines mark the calibration goal of ± 7.5 km s\(^{-1}\).
4.1 COS-to-STIS Results

Figures 10 and 11 show the residual errors vs. XFULL location across the detector for the COS-to-STIS cross-correlations of COS data calibrated with the previous DISPTAB (purple circles) and the updated DISPTAB (black stars). In most cases there is very obvious improvement to within ±3 pixels (orange dashed lines). The effects of gain sag at lower pixel numbers for FUV A are still present since they are not removed by the wavelength solutions. The most dramatic differences in improving systematic slopes across the detectors can be seen in the 1327 and 1623 settings. Even though the data for 1327/FUV A, 1589/FUV A, 1600/FUV A, and 1623/FUV A were insufficient to contribute to the final wavelength solutions, we still calculated the residuals for the limited number of data points we had for those settings and find there is improvement in the calibration.

Figure 10. COS-to-STIS cross-correlation residuals for G130M, all updated cenzwaves and segments. The residuals from the corrected DISPTAB (black stars) are now within ±3 pixels (~7.5 km s⁻¹) while for the old DISPTAB (purple circles) they are within ±6 pixels (~15 km s⁻¹). Multiple targets and FP-POS were used for different settings. The 1327/FUV A data were not used in the ray-trace fit to derive the final dispersion coefficient.
Figure 10. (Continued.)

Figure 11. Same as Figure 10 for COS-to-STIS cross-correlation residuals for G160M, all updated censwaves and segments. The 1589/FUVA, 1600/FUVA, and 1623/FUVA data were not used in the ray-trace fit to derive the final dispersion coefficients.
Figure 11. (Continued.)
4.2 COS-to-COS Results

Once the final zero points were obtained, the COS-to-COS cross-correlations were performed using the new DISPTAB to determine the accuracy of the new zero points. Figures [12] to [15] show examples of the distribution of residuals for neighboring and extreme cenwave pairs using the SMOV, intermediate, and final DISPTAB calibrations. The errors are indicative of the relative wavelength alignment between different cenwaves for a grating/segment mode when performing data-processing with CalCOS. In general, the intermediate DISPTAB reduces the scatter in the residuals and removes the systematic tilt across a segment, due to the improvement of the dispersion terms. The final DISPTAB eliminates the absolute offset of residuals because of the zero point update. The improvements tend to become more significant with the increasing difference between the cenwaves. COS-to-COS residual error plots for all of the cenwave combinations can be found in Appendix B.

Figure [16] summarizes the mean shifts and standard deviations with the old SMOV DISPTAB (green) and newly updated one (purple). There is an improvement in both the mean and standard deviation in most settings, indicating that the overall uncertainties in the wavelength calibration are now within ± 3 pixels.
Figure 12. Examples of COS-to-COS cross-correlation residual error distributions for two FUVA G130M neighboring (top panels) and extreme (bottom panels) cenwave combinations, with the SMOV (left), intermediate (middle), and final (right) DISPTABs. Orange shows the ± 3 pixel goal, and blue, the measured one-sigma uncertainty.
Figure 13. Same as Figure 12 for distributions of COS-to-COS cross-correlations for G130M FUVB.
Figure 14. Same as Figure 12 for distributions of COS-to-COS cross-correlations for G160M FUVA.
Figure 15. Same as Figure 12 for distributions of COS-to-COS cross-correlations for G160M FUVB.
Figure 16. Average residuals for all COS-to-COS correlations (top: FUVA; bottom: FUVB) with the updated DISPTAB (purple) and the old DISPTAB (green). The number of windows included in the cross-correlation for each setting is given above (new) and below (old) each point. These numbers can differ depending on where the window fell in relation to a DQ flag.
5. Reference File Details

For LP2, the DISPTAB name delivered with this effort is 0bn1606sl Disp.fits. In the DISPTAB, the D and D TV03 values (Oliveira et al. 2010) are set to zero for the revised modes because they were absorbed into the new zero-point coefficient. For all updated cenwaves, the BOA values were copied from the PSA. All cenwaves in the previously non-LP dependent DISPTAB are present in the new DISPTAB regardless of whether data are currently in the archive for them at LP2. G130M/1055, 1096, 1222 and G140L/1105, 1230, 1280 values were copied from the old DISPTAB, xaa18189l Disp.fits, because these modes were not updated in this effort. The header was also updated to include a LIFE_ADJ header keyword equal to 2, since this DISPTAB is only to be used with LP2 data.

6. Conclusions

On November 11, 2016, the dispersion coefficient and zero-point values at LP2 were updated for cenwaves G130M/1291, 1300, 1309, 1318, 1327 and G160M/1577, 1589, 1600, 1611, 1623. Compared to our similar study for LP1, the LP2 datasets had two main deficiencies that required additional examination and treatment: a lack of sufficient data to derive wavelength solutions at some cenwaves, and gain sag at the short-wavelength end in FUV A that distorted the solutions. An analysis of ray-trace models found that the variation of dispersion with cenwave is driven mainly by linear focus offsets applied to maintain resolution for each cenwave. Thus, to fill in missing cenwaves in the LP2 data and improve the statistical results, dispersion terms from LP2 COS-to-STIS cross-correlations were fit with ray-trace models as a function of OSM1 focus position combined with LP1 values. For FUV, data with XCORR < 3400 were eliminated from the computations, since walk corrections along the dispersion direction are not applied yet to overcome gain-sag effects. Zero points were further adjusted by using archival LP2 COS data for which cross-correlations were performed between differing cenwaves within the same visit. These solutions were tested by calibrating all data with the updated DISPTAB and verifying that the residuals were all properly centered around zero with no residual slope. With these new solutions, the accuracy of the COS wavelength solution has improved from 6 pixels (~15 km s^{-1}) to 3 pixels (~7.5 km s^{-1}). This error estimate does not include any additional errors due to target acquisition or other FUV detector effects such as walk. G140L grating wavelength solutions may need to be updated in the future, but the current wavelength accuracy of this grating (250 km s^{-1}) satisfies the scientific needs of the community, whereas the G130M and G160M gratings are more frequently used with science goals that need a very accurate wavelength scale. All archival COS LP2 data were reprocessed using the file 0bn1606sl Disp.fits in November 2016. Further discussions of work on the wavelength solution improvements for other lifetime positions can be found in separate documents.
Change History for COS ISR 2018-23

Version 1: 18 February 2019 – Original Document

References


Appendix A. Effects of OSM1 Configuration on FUV Dispersion

Since the LP2 wavelength calibration required revised methods to handle some limitations of the FUVA archival datasets, we undertook a study of ray-trace models to understand the effects of the Optics Select Mechanism 1 (OSM1) configuration on dispersion coefficients. The OSM1 places one of four optical elements into the beam from the HST secondary mirror: three gratings reflect spectra to the FUV detector (G130M, G160M, and G140L), and one mirror directs light to the OSM2 mechanism and then onto the NUV detector. The COS spectroscopic mode is selected by rotating one of the optical elements into the light path to the instrument. In addition to rotation, the OSM1 also can be translated along the beam to provide focus adjustments.

For the FUV gratings, a rotation step moves the spectrum by \(\sim 250\) pixels on the detector. The locations of the standard cenwaves (G130M/1291, 1300, 1309, 1318, 1327 and G160M/1577, 1589, 1600, 1611, 1623) are four steps apart, while FP-POS locations are one step apart. Focus positions are different for each cenwave to maximize the spectral resolution, but all FP-POS exposures for a cenwave are taken at the same focus. For the standard cenwaves, the OSM1 is translated by a +170 focus-step offset with each increasing cenwave value. These configuration states are built into the ray-trace models for wavelength solutions.

For the LP1 wavelength calibration (Plesha et al. 2018), ray-trace models were generated for each cenwave only at FP-POS=3, which is the location at which the wavelength solutions are applied. (CalCOS shifts exposures at other FP-POS positions to FP-POS=3 through the LAMPTAB templates.) We have recalculated these models for both LP1 and LP2 to include all four FP-POS positions for each cenwave to further examine the dependence of dispersion on OSM1 settings. As before, dispersion coefficients were calculated at a nominal zero focus configuration, which includes the 170 step focus change between each cenwave, and at ±100, 250 and 500 steps offset from it. In Figure A-1 we show the values for the zero and ±250 focus positions. The dashed lines connect the FP-POS=3 dispersion coefficients. The abscissa values are the OSM1 rotation locations, LOSM1STP, where the FP-POS=3 position for each cenwave is given in Table A-1 and FP-POS=(1,2,4) are (−2,−1,1) steps from it, respectively.

The models indicate that, as the focus increases, so does the dispersion. The sense of focus motion is that a positive step moves the grating closer to the COS aperture and HST secondary mirror. This also moves the grating closer to the detector, and since the FUV channel is essentially a Rowland circle spectrograph, this causes each pixel to encompasses a larger piece of the spectrum, i.e., the dispersion becomes larger. The FP-POS dispersion values for each cenwave are nearly the same for FUVB, but for FUVA, there is a noticeable effect of OSM1 rotation, with the FP-POS=4 values being greater than those at FP-POS=1.
Table A-1. OSM1 Rotation Positions for Each Cenwave at FP-POS=3

<table>
<thead>
<tr>
<th>Grating</th>
<th>Cenwave</th>
<th>LOSM1STP</th>
<th>Grating</th>
<th>Cenwave</th>
<th>LOSM1STP</th>
</tr>
</thead>
<tbody>
<tr>
<td>G130M</td>
<td>1291</td>
<td>7999</td>
<td>G160M</td>
<td>1577</td>
<td>11203</td>
</tr>
<tr>
<td>1300</td>
<td>7995</td>
<td></td>
<td>1589</td>
<td>11199</td>
<td></td>
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<tr>
<td>1309</td>
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<td>7983</td>
<td></td>
<td>1623</td>
<td>11187</td>
<td></td>
</tr>
</tbody>
</table>

Figure A-1. Dispersion values from LP2 ray-trace models for every cenwave and FP-POS vs. OSM1 rotation position (LOSM1STP, see text and Table A-1). Black circles are the nominal zero focus position, red triangles are the +250 step focus offsets, and blue squares are −250. Dashed lines connect FP-POS=3 values.

Figure A-2 shows the dispersion values for FP-POS=3 as a function of OSM1 focus instead of rotation. The focus values for the ray-trace models are relative, so we have assigned on-orbit LP2 values to the nominal zero-focus configuration and added ± 250 steps to those for the other two models. We find that for FUVB the dispersion...
coefficients fall on a single relation for each grating. For FUVA, the ± 250 curves are parallel to, but offset from, the nominal focus due to the OSM1 rotation dependence. Overall this analysis shows that the main driver of the dispersion value variations is the focus position of OSM1. Because the G130M baseline focus at LP2 was offset by +120 steps from LP1 and +160 steps for G160M, the rotation effects of FUVA will be smaller than in Figure A-2 when comparing the LP1 and LP2 dispersion coefficients. We expect them to be comparable to the error in dispersion measurements, since each cenwave can include a different variety of FP-POS from the archival datasets.

![Image](image-url)

**Figure A-2.** LP2 model dispersion values for FP-POS=3 vs. OSM1 focus position.

We can determine the effect of OSM1 rotation by removing the changes due to the 170-step focus offset between cenwaves. In Figure A-3, we show the dispersion coefficients for the nominal zero-focus models as in Figure A-1 and the adjusted values after removing the contributions from the focus offsets, calculated by scaling the shifts from the +250 step model to +170 steps. Since the shifts are relative, we arbitrarily set the focus offset to be zero at the initial cenwave for each grating such that the curves appear to be normalized at that mode. As noted before, FUVB dispersion coefficients have little dependence on OSM1 rotation, while FUVA is found to have a nearly linear relation. This would imply that FUVA should be calibrated with wavelength solutions as a function of FP-POS, but the overall impact on the wavelength scale is small.
The dispersion coefficients change by $\delta_{\text{rot}} = 3.2 \times 10^{-4}$ (G130M) and $3.9 \times 10^{-4}$ (G160M) mA/pixel/step. Thus, the center-to-edge difference between FP-POS=1 and 4 exposures would be $\delta_x \sim 3 \times \delta_{\text{rot}} \times 7150/a_1$, where the active area of a segment is $\sim 14300$ pixels and $a_1$ is the mean dispersion. This difference is $\sim 0.9$ pixel, much smaller than a resolution element.

Figure A-3. Effect of OSM1 rotation on the LP2 ray-trace model dispersion coefficients. Black circles are the nominal zero focus values (Fig. A-1), and red circles are the values with the on-orbit 170-step focus offsets removed.

Finally, these rotation curves can be tested against observations by comparing them to the wavelength solutions derived during TV03 ground testing, where the focus was not changed between cenwaves for the exposures. In Figure A-4 we show the TV03 dispersion relations with fits of the rotation-only ray-trace model values. As with the LP1 and LP2 wavelength calibration, the curves can be moved vertically since the models have an arbitrary zero-point reference. We find that the fits are satisfactory and follow the measured TV03 values. Thus, the ray-trace models resolve the question of why the wavelength calibration from SMOV had systematic errors. The original on-orbit calibration used the TV03 wavelength solutions and only adjusted the zero points due to the final alignment of COS into the HST optical path (Oliveira et al. 2010). The ground-based dispersion coefficients were determined at a constant focus, whereas on-orbit exposures are taken at focus positions dependent on the cenwave used.
Figure A-4. Fit of OSM1 rotation models from Fig. A-3 (red dashed line) to the TV03 measured dispersion coefficients.
Appendix B. COS-to-COS Cross-Correlation Residual Error Plots

This appendix presents figures showing the COS-to-COS cross-correlation results of G130M and G160M for all available cenwave combinations at LP2. As discussed in Section 4.2, distributions of residuals for cenwave pairs were determined for wavelengths assigned using the old DISPTAB from SMOV, the intermediate DISPTAB (Section 3), and the final DISPTAB from this study. These statistics illustrate the relative alignment between cenwaves that is now achieved. The orange region indicates the new goal of $\pm 3$ pixels, while the blue region shows the one-sigma uncertainty. The number of windows included in the cross-correlation can differ depending on where a window fell in relation to a DQ flag. With the new DISPTAB, the residual slopes disappear and the centering of the distributions fall closer to zero, with the improvement becoming more significant for cenwaves that are further away from each other, e.g., 1291 vs. 1327.
Figure B-1. Cross-correlation distributions of FUVA G130M cenwave combinations for which data were available.
Figure B-1. (Continued.)

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Figure B-1. (Continued.)

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Figure B-1. (Continued.)
Figure B-1. (Continued.)
**Figure B-2.** Cross-correlation distributions of FUVB G130M cenwave combinations for which data were available.
Figure B-2. (Continued.)
Figure B-2. (Continued.)

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Figure B-2. (Continued.)
Figure B-2. (Continued.)
Figure B-3. Cross-correlation distributions of FUVA G160M cenwave combinations for which data were available.

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Figure B-3. (Continued.)
Figure B-3. (Continued.)

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Figure B-3. (Continued.)
Figure B-3. (Continued.)

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Figure B-4. Cross-correlation distributions of FUVB G160M cenwave combinations for which data were available.

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Figure B-4. (Continued.)

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Figure B-4. (Continued.)
Figure B-4. (Continued.)
Figure B-4. (Continued.)