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Testing for Systematics when moving the COS Aperture Block

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ABSTRACT In preparation for the move to COS FUV Lifetime Position 5 (LP5) and future LPs located above $+5.4''$, we verify that there are no systematic effects introduced by calibrating science exposures taken at LP5 ($+5.4''$) with wavecal exposures taken at LP2 ($+3.5''$). We demonstrate this using a cross-correlation technique that quantifies the accuracy with which Pt-Ne lamp spectra return to the same position in the dispersion (x) and cross-dispersion (y) directions after the aperture block moves between LP2 and LP5. We find that successive LP5 exposures separated by aperture moves are aligned at the 0.1–0.4 pixel level in x, and that these small offsets can be explained by OSM drift, and at the 0.026 pixel level (1σ) in y, indicating the movement is reproducible. Together these results indicate that calibrating COS FUV science data taken at LP5 with lamp flash data taken at LP2 would not adversely affect the wavelength calibration or spectral resolution of the data.

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1. Introduction

COS science exposures are wavelength-calibrated using lampflash exposures taken with the Platinum-Neon (Pt-Ne) lamp. For routine operations at the first four Lifetime Positions (LP1 to LP4) of the COS FUV detector, lampflash exposures were taken at the same LP as the science exposures. This allowed the Pt-Ne lamp to be flashed during the exposure without any movement of the aperture block. However, for positions at or above $+5.5''$ on the detector, such operations are not possible, because the FUV light leak[1] (Oliveira et al. 2013) prevents lampflash exposures being taken at the same position as the science exposures. As a consequence, lampflash exposures in such cases must be obtained at a different LP. LP2 is a natural choice since it is the closest existing position on the detector to LP5, although the exact choice of location for LP5 operations is yet to be determined at the time of publication of this ISR.

Taking lampflash exposures at a different LP than the science exposures presents two challenges. First, it introduces additional overhead, because of the time taken to physically move the aperture block and the time taken to take the actual lamp exposures (which previously were taken simultaneously with the science). Second, it may introduce systematic offsets in the location of the spectra on the detector, because if the aperture block does not return to precisely the same position, there may be small differences in the optical path between successive LP5 exposures, which could in principle degrade both the wavelength alignment and the spectral resolution of the science data.

The purpose of this ISR is to report the results of an investigation into this aperture-shift effect, and to quantify the magnitude of any systematic effects introduced by moving the aperture block to conduct wavecal exposures. We analyze data taken under the special calibration Program ID 16052 (PI Bethan James), "Testing for Systematics when moving the COS Aperture Block". We also separate the effects of OSM drift (an effect in the dispersion direction) from aperture shift (a separate effect in the cross-dispersion direction.

2. Observations and Program Design

Program 16052 executed as a single three-internal-orbit *HST* visit on December 1, 2019. The visit began with an initial 2000s G160M/1577 lamp-settling exposure to minimize drift, which follows from movement of the OSM1 wheel. The last movement of the

[1]The light leak occurs when light from the Pt-Ne lamp passes through the FCA aperture. In general, an aperture mask covering the FCA prevents the light leak, but since the mask remains fixed when the aperture block moves, a position is reached (at or above $+5.5''$) where the mask does not fully cover the aperture, precluding the use of the Pt-Ne lamp.

OSM1 wheel before this settling exposure was NCM1-to-G160M, a movement that has been shown to result in low drift. We then took a set of 5x50s lamp exposures at LP2 ($+3.5''$) followed by a set of 5x50s at LP5 ($+5.4''$). (Note that when we refer to lamp exposures at LP2, we mean at the WCA position for LP2, which is $9''$ above the PSA; the $+3.5''$ refers to the PSA position. The same applies to LP5: $+5.4''$ refers to the PSA.) We then repeated the entire sequence five times, giving five sets of LP2 exposures and five sets of LP5 exposures. Note that the final choice of LP5 position may differ from $+5.4''$, but for the purposes of this ISR we will refer to $+5.4''$ as LP5, for convenience. All exposures were taken with the G160M/1577/FUVA setting and FP-POS=4, which ensured that the OSM1 wheel was not moved during the visit after the initial lamp-setting exposure, therefore minimizing drift. In addition, the visit was designed in APT to be non-interruptible to maintain a continuous exposure and further minimize drift.

The lamp exposure times were commanded in APT using the optional parameter FLASH=S0200D050, where the final three digits (050) refer to the exposure time in seconds and the first four digits (0200) refer to the duration of the flash sequence in seconds, meaning that the sequence was 50 s on, 150 s off. The choice of 50 s exposure times was designed to provide ≈20–30 counts in the PtNe-lamp emission lines in the G160M/1577 region, where the count rate per line is ≈0.4–1 cts s^{-1}. A range of 20–30 counts per line enables an accurate cross-correlation (Plesha et al. 2018); longer exposures could potentially have overheated the lamp. To move the aperture between LP2 and LP5, we used special commanding with the ALIGN/APER exposure command in APT. The parameter "QESIPARM XSTEPS -40" was invoked to move from LP2 to LP5, where the number of aperture motor steps of -40 was calculated using the difference of $1.9''$ between LP2 and LP5 and the scale of 21 steps per arcsecond. We checked the telemetry values and verified that the aperture readback values were as expected after each move.

Standard calibration was bypassed for the visit because LP5 reductions were not enabled in the standard pipeline at the time the program executed (in particular, the LP5 extraction box was not defined). Instead, we ran the CalCOS pipeline manually up to the `corrtag` stage using customized extraction boxes and a BOXCAR reduction. We then collapsed the counts along the cross-dispersion direction to compute the run of counts against XCORR (corrected x-pixel coordinate), and then along the dispersion direction to compute the run of counts against YCORR. We coadded each set of 5x50s lamp exposures (five sets at LP2 and five at LP5), and our subsequent analysis is based predominantly on these ten coadds, although as an additional check we also perform an analysis of individual 50 s exposures in section 3.2. The coadds are referred to using the following notation: LP2(1) refers to the first coadd at LP2, LP2(2) refers to the second, LP5(1) refers to the first coadd at LP5, and so on.

3. Analysis

Our analysis is split into three parts. First, we investigate the level of OSM drift within each set of five exposures using the "DISP_SHIFT" value returned by CalCOS. Second, we investigate the aperture-shift effect in the dispersion direction, by cross-correlating various pairs of exposures and quantifying their alignment. Third, we investigate the aperture-shift effect in the cross-dispersion direction, by determining the centroid of each set of exposures in the y-direction and looking for variation between each set.

3.1 Drift

We determined the level of drift in the dispersion direction during each exposure using the DISP_SHIFT value measured by CalCOS, which represents the pixel offset between each lamp-flash exposure and the lamp template (which was taken at LP1). We observed a $\approx$0.5 pixel offset (determined by eye) in the values of DISP_SHIFT between the LP2 and LP5 exposures, in the sense that the LP5 values were 0.5 pixels lower than the LP2 values. We assume that this offset is due to optical effects arising because the LP2 and LP5 spectra fall in physically different regions but the template was taken in yet another position (LP1). In Figure 1 we plot the value of DISP_SHIFT during each set of exposures, with the LP5 values corrected by this offset of +0.5 pixels.

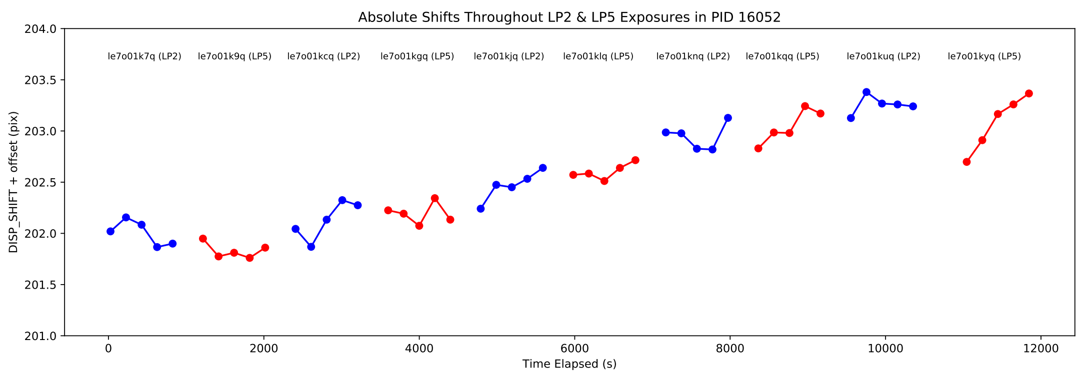

Figure 1. Absolute pixel shifts (drift) reported by CalCOS during the ten sets of lamp flash exposures taken in program 16052. A +0.5 pixel offset has been applied to all the LP5 pixel shifts. LP2 (LP5) exposures are shown in blue (red) circles. An overall drift of $\approx$1.2 pixel over 12 000 seconds is present, as indicated by the positive slope. However, the size of the drift is <0.2 pixels within all sets of exposures except the final one, where it reaches 0.75 pixels.

A drift of $\approx$1.2 pixels is present across the entire visit, as shown by the positive slope of the data. However, within each set of five exposures, the size of the drift is very small: <0.2 pixels in all sets of exposures except the final set at LP5, where it reaches $\approx$0.75 pixels. The good alignment between each set of LP2 and (offset-corrected) LP5 datapoints (i.e. the continuous trend between each set of red and blue points) already suggests that the aperture movement does not introduce any substantial offsets in the location of the spectra in the dispersion direction. This is explored in more depth in the next sub-section using cross-correlations.

3.2 Aperture shift effect in dispersion direction

We developed an IDL routine (`apshift.pro`) that quantifies the degree of alignment in pixel space of different pairs of spectra (5×50 s). In general, we use the code to compare *coadded* spectra, not individual spectra, since the S/N in the coadds is higher, maximizing the number of emission lines that contribute to the cross-correlation, and also because the level of drift within each set of exposure is very small (section 3.1). The routine cross-correlates the two spectra in the pair to produce a global cross-correlation function (CCF). Only counts in the active region of the detector are included (taken here to be XCORR between 1500 and 15000). We then fitted a Gaussian function to the CCF to determine its centroid (in pixels). The centroid of the CCF quantifies the mean offset between the two spectra: a mean offset of zero means perfect alignment, and a mean offset of 1 indicates misalignment at the level of 1 pixel. The results are shown in Table 1 for different pairs.

Table 1.: Summary of Cross-Correlation Results

First Coadd	Second Coadd	Mean Offset (pixels)	Note
LP2(1)	LP5(1)	0.43	first LP2 set to first LP5 set
LP2(2)	LP5(2)	0.22	
LP2(3)	LP5(3)	0.08	
LP2(4)	LP5(4)	0.21	
LP2(5)	LP5(5)	0.51	
LP2(1)	LP2(2)	−0.19	first LP2 set to second LP2 set
LP2(2)	LP2(3)	−0.32	
LP2(3)	LP2(4)	−0.54	
LP2(4)	LP2(5)	−0.36	
LP5(1)	LP5(2)	−0.40	first LP5 set to second LP5 set
LP5(2)	LP5(3)	−0.45	
LP5(3)	LP5(4)	−0.39	
LP5(4)	LP5(5)	−0.07	
LP2(1)	LP5(5)	−0.90	longest time baseline
LP2(1_5)	LP5(1_1)	0.14	shortest time baseline

We analyzed several different pairs of coadds for different reasons. First, we compared each LP2 coadd with the subsequent LP5 coadd, to investigate whether any aperture shift is present between a science spectrum (at LP5) and its preceding lamp exposure (at LP2). These results are shown in the first five rows of Table 1). Second, we compared each LP2 coadd with the subsequent LP2 coadd (next four rows), and each LP5 coadd to the subsequent LP5 coadd (next four rows), to quantify the reproducibility of the aperture mechanism in returning to the same position. Third, we compared the first LP2 coadd with the final LP5 coadd, to give the pair with the longest time baseline (12 000 s), to look for any cumulative effect that could build up over time. Finally, we compared the final (fifth) *individual* 50s exposure in the first set of LP2 exposures –

denoted LP2(1_5) – with the first exposure in the first set of LP5 exposures – denoted LP5(1_1) – to give the exposure pair with the shortest time baseline. This final test also tested the procedure at the individual exposure level (50 s), not the coadd level (5×50 s). Three example pairs showing the cross-correlation technique are given in Figure 2.

The main result seen in Table 1 is that all of the pixel offsets are small, typically in the 0.1–0.5 pixel range, indicating the two spectra are aligned at this sub-pixel level. The largest offset observed is -0.90 pixels, between the first LP2 coadd and the fifth LP5 coadd, observed 12 000 s later. The offsets are observed to be small for each set of pairs investigated: LP2-LP5 pairs, the LP2-LP2 pairs, and the LP5-LP5 pairs. One result worth noting is that all the LP2-LP2 pairs have negative offsets, and all the LP5-LP5 pairs have negative offsets (the sign of the offsets is not important, because it depends which spectrum is treated as the reference in the cross-correlation; what matters is that all these pairs have the same sign). This indicates that each successive coadd is slightly offset from the one before, but only at a sub-pixel level. This is exactly the same effect seen in the slope in Figure 1, which showed that a low, steady drift was present throughout the visit. *We conclude that the small, sub-pixel offsets between successive LP2 exposures and between successive LP5 exposures are due to OSM drift alone, not aperture shift.* The finding that the largest offset is seen in the pair with the longest time baseline [LP2(1) to LP5(5)] further supports this interpretation.

There are no trends in alignment with wavelength apparent in the data. We verified this by splitting up the spectra into chunks of 2000 pixels, and repeating the cross-correlation analysis on each of these small regions. The results from this exercise are annotated for each pair shown in Figure 2 under the heading "local offsets".

3.3 Aperture shift effect in cross-dispersion direction

In this section, we determine whether aperture shifts have any effect on the alignment of the spectra in the cross-dispersion (y) direction. The repeatability of the LP2 position is particularly important, because the wavecal lamp fills the aperture, so if the LP2 position is offset, the wavecal will appear at an offset location on the detector. In contrast, when we take an external spectrum at LP5, a slight error in the position of the aperture will not matter because all of the light still makes it through the aperture, at least for point sources.

To investigate this, we collapsed each coadded lamp spectrum along the x-direction to form its cross-dispersion profile, in units of counts vs YCORR. We then fit Gaussians to the cross-dispersion profiles to determine the central y-position of the spectrum. We repeated this for the five LP2 coadds and the five LP5 coadds, and measured the standard deviation of each set. This standard deviation quantifies the reproducibility of the alignment of the spectra in y. This is shown in Figure 3. We found that the 5 LP5 exposures are aligned at the 0.026 pixel level, and the 5 LP2 exposures are aligned at the 0.092 pixel level, slightly larger but still small enough to be unproblematic.

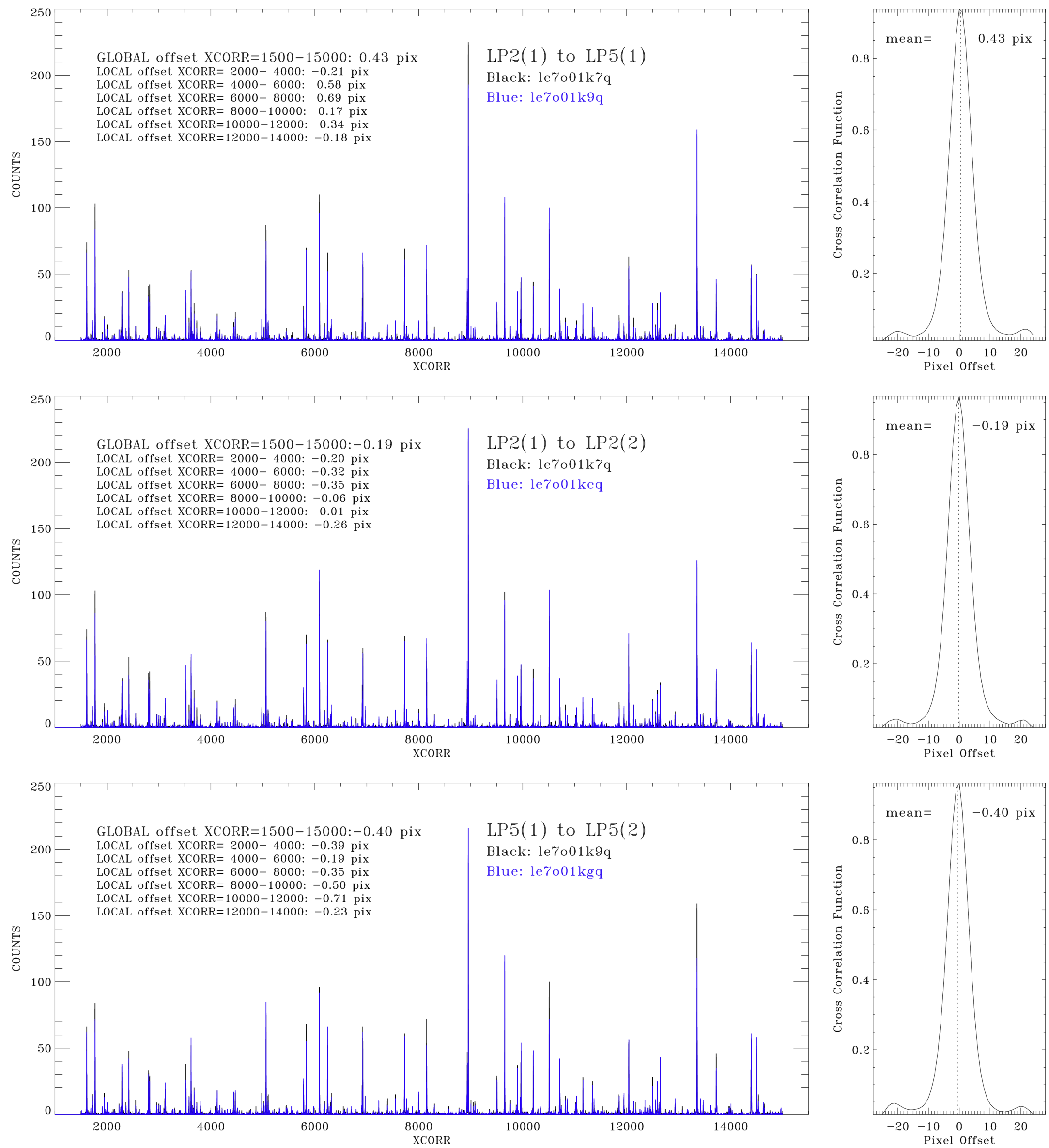

Figure 2. Illustration of the cross-correlation technique used to verify the alignment of different pairs of exposures. Three pairs are shown: **Top:** First LP2 coadd [LP2(1)] with the first LP5 coadd [LP5(1)]. **Middle:** First LP2 coadd with second LP2 coadd. **Bottom:** First LP5 coadd with second LP5 coadd. In each case, the main panel shows the two lampflash spectra being compared in blue and black, and the right panel shows the global cross-correlation function (CCF) of the two spectra; the centroid of a Gaussian fit to the CCF yields the mean offset of the two spectra, as annotated on the plot and summarized in Table 1. The inset tables in each figure show the results from *local* cross-correlations in 2000-pixel windows, to check for any wavelength dependencies.

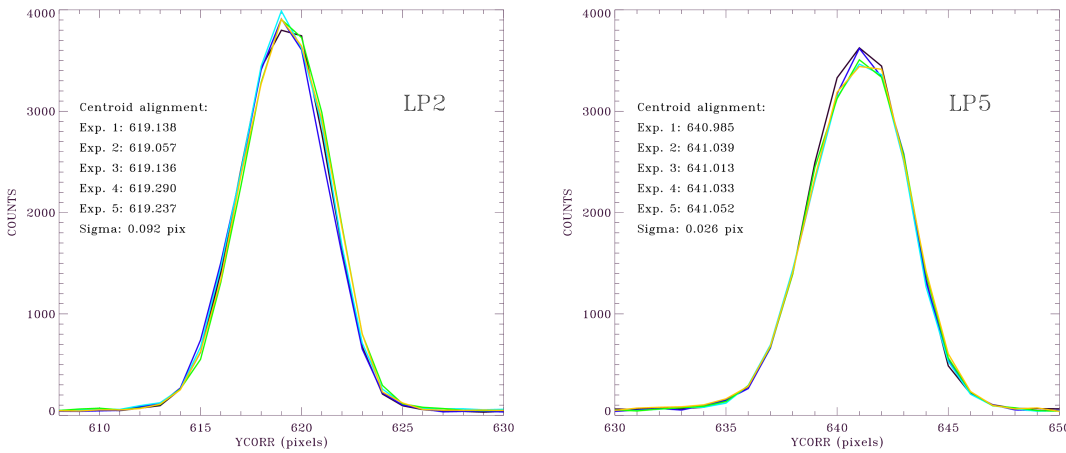

Figure 3. Alignment of the coadded lamp spectra in the y-direction. The figures show the cross-dispersion profile of the coadded lamp spectra. The left panel shows the five LP2 coadds, and the right panel shows the five LP5 coadds. The Gaussian centroids of each profile are annotated on each panel.

4. Summary

In this ISR we analyzed the data taken under Program 16052 to investigate whether the wavelength alignment of COS FUV exposures taken at LP5 (here represented by spectra taken at $+5.4''$) is degraded by by moving the aperture block to take wavecal exposures at LP2 ($+3.5''$). The reason for investigating this "split-LP" mode of operations is that the light leak occurring when the aperture is placed above $+5.4''$ prevents simultaneous wavecal exposures being taken, necessitating a different mode of wavelength calibration. Using a cross-correlation analysis, we determined the following results:

- In the dispersion direction, pairs of LP5 exposures taken with a detour to LP2 in-between are aligned in the dispersion direction at the 0.1–0.4 pixel level. LP5-LP5 pairs and LP2-LP2 pairs are aligned at similar accuracy of 0.1–0.5 pixel. All of these small offsets can be attributed to drift, because they match the offsets reported by the SHIFT_DISP value returned by CalCOS. Furthermore, these small offsets are well within the overall COS FUV wavelength error budget of 3 pixels (Plesha et al. 2018).

- In the cross-dispersion direction, the five LP5 exposures are aligned at the 0.026 pixel level, and the five LP2 exposures are aligned at 0.092 pixel level, indicating that the aperture mechanism returns the spectrum to the same place on the detector with good reproducibility.

In conclusion, we have shown that aperture movements of magnitude $1.9''$ only impact the location of the spectra on the FUV detector by sub-pixel levels, with a range of $\approx$0.1–0.4 pixels, well within the wavelength-scale error budget, and that these small offsets can be attributed to drift. These results indicate that calibrating data taken at $+5.4''$ with lamp spectra taken at LP2 does not introduce a noticeable effect on wavelength accuracy or spectral resolution, and therefore that split-LP operations are feasible.

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References

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