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# Investigating the Long-term Repeatability of the COS OSM1 Mechanism 

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#### Abstract

The Optics Select Mechanism 1 (OSM1) in the COS instrument is responsible for placing the spectrum on the FUV XDL detector along the dispersion direction in a repeatable way, to a required accuracy of better than half an FP-POS, or $\sim 125$ detector pixels. In May 2022, the COS team detected two separate changes in OSM1 motions. First, within the G130M grating positions at the 1291 central wavelength, small OSM1 motions ( 1 motor step) to the $F P-P O S=3$ and $F P-P O S=4$ locations resulted in spectral placement that was offset ( $\sim 120$ pixels) and less precise ( $\sigma=25$ pixels to $\sigma=$ 40 pixels) than large OSM1 motions ( $>200$ motor steps) to these locations. This behavior began at the start of LP4 operations, and impacts the gain sag holes on the detector due to geocoronal Lyman alpha emission falling on different locations of the FUVB segment. Second, at the 1222 central wavelength, the FP-POS $=2$ and 4 locations showed a significant positive trend with time in spectrum positioning at a rate of nearly 0.5 pixels/day for close to six months before flattening out. Since this 1222 behavior was directly correlated with a change in OSM1 home position, the COS team hypothesized this change may be the cause of a significant fraction of the behavior. Aside from slightly larger gain sag holes, these changes in OSM1 motions have minimal science impacts on COS data, although users who are concerned with precise spectral placements on COS FUV might want to consider mitigation strategies.


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## 1. Introduction

The COS instrument relies on several mechanisms to place light from a target source accurately on both the NUV-MAMA and FUV Cross Delay Line (XDL) detectors. One of these mechanisms, the Optics Select Mechanism 1 (OSM1), is responsible for placing spectra in a repeatable fashion along the dispersion direction for FUV observations and serves to pass light to the NUV side of the instrument via the NCM1 mirror. This ISR discusses the long-term repeatability of OSM1 across several COS gratings and central wavelength settings (cenwaves), with a focus on those cenwaves where significant trends or non-repeatabilities are observed. In Sections 1.1-1.2, we discuss the use of OSM1 during a science observation through on-board commanding, as well as the history of OSM1 usage, including how issues with repeatability were addressed previously. In Section 2, we describe how spectrum placement on the detector is measured and monitored. In Section 3, we detail the discovery by the COS team of anomalous spectral placements that were large enough to warrant a detailed study on the cause and impact. In particular, significant non-repeatability and offsets in spectral position were found for G130M/1291 FP-POS $=3$ and 4, and systematic trends
in spectral placement were observed in both G130M/1222 FP-POS=2, 4 and in G140L/800. In Section 4 we list the possible mechanical explanations for the cause of these behaviors, coming to the conclusion that the strongest correlation is with the STScI home position location, the location on the wheel that OSM1 returns to after a series of observations. We also list additional open questions and recommendations for further study.

A separate ISR, Debes et al. 2023, describes the change in home position (from G130M/1222 to G130M/1291) to mitigate the observed behaviors and dedicated monitoring.

### 1.1 OSM1 position in the COS light path

Figure 1 shows an example light path for both the FUV and NUV channels of COS. For an FUV observation, the light travels through the selected aperture after the aperture block has been moved to compensate for the observatory pointing required to place the spectrum at the proper cross dispersion location on the detector, or "lifetime position" (LP). The light then arrives at OSM1, which has been rotated such that the selected grating (e.g., G130M) is in the path of the incoming light, and a spectrum is then transmitted to the XDL detector. In an NUV observation, OSM1 is rotated to the NUV Collimating Mirror 1 (NCM1) position and light travels first to NUV Collimating Mirror 2 (NCM2), arriving at Optical Select Mechanism 2 (OSM2). There, NUV gratings for COS are selected and the resulting spectrum is placed on the NUV-MAMA detector after a final reflection off of the three NCM3 mirrors.

## COS light path



Figure 1. The COS light path. The OSM1 is a rotary mechanism that is reponsible for either placing a spectrum on the FUV detector via one of the gratings (G140L, G130M, or G160M) or reflecting the light to the NUV detector via the NCM1 mirror.

### 1.2 OSM1 Description, required accuracy, and preferred direction

The COS OSM1 was constructed by Ball Aerospace using motors obtained from CDA Intercorp in Deerfield, FL. The OSM1 consists of two systems that are responsible for changing gratings via a rotary mechanism and changing focus via a linear mechanism. More details are located in COS SE02 (Osborne 2004). We provide a high level description of the rotary mechanism from that document here to orient the reader.

The rotary assembly consists of a stepper motor that has 30 degree steps directly attached to the optics wheel through a flexible coupling with a gear ratio of $1066^{2 / 3}$ such that one revolution of the optics wheel is $1066^{2} / 3$ revolutions of the motor. The motor completes one revolution in 12 steps, giving a total of 12800 possible motor step positions (see Figure 2). While the mechanism does not have hard physical stops, the flight software for COS sets soft limits at steps 50 and 12749. The mechanism moves in a "preferred" direction, with the G140L grating corresponding to the lowest motor steps, followed by NCM1, G130M, and finally G160M. The COS cenwaves used within each grating and their corresponding motor steps are indicated in Figure 2.

Within a given cenwave and grating combination, a single motor step between successive FP-POSs results in differences of $\sim 250$ pixels on the detector in the dispersion direction, with the exact distance determined by the details of each grating and its mounting. Coarse and fine motor resolvers report the position of the motor to resolutions of 20 arcseconds ( $\sim 50$ pixels) and 0.5 arcseconds ( $\sim 1.25$ pixels), respectively as part of the instrument telemetry.

OSM1 relies on a combination of friction and magnetic force to ensure that the motor stops at a particular step. Temperature within the assembly, lubrication distribution, and usage patterns could conceivably impact how these two physical situations might interplay with repeatability of the mechanism in positioning a spectrum on the detector. The OSM1 motors are capable of overheating, thus the full assembly contains temperature sensors that will trigger an overheat condition if the temperature becomes too high. COS will safe if any of the motors (OSM or aperture mechanism) are above $55^{\circ} \mathrm{C}$, and if the temperature is above $62^{\circ} \mathrm{C}$, the motor winding relay is opened and all commands to move the motor will be ignored until the temperature drops below the threshold. Repeated large motions can in principle raise the temperature of the motor by 1-2 degrees, which may also be important for how well the mechanism is able to stop.

The requirement for positioning accuracy of OSM1 is half a step size ( $\sim 125$ detector pixels), as the spectra at different FP-POSs would otherwise overlap. However, historically the actual accuracy for most modes has been significantly better than this. For example, from LP1 to LP3, the standard deviation of spectral placement locations for G130M/1291 was just $\sim 15$ pixels, a factor of $\sim 8$ smaller than the accuracy requirement.

### 1.3 OSM1 Repeatability before Launch and the "Song and Dance" Moves

During ground testing, it was found that non-repeatabilities in OSM1 moves were significant enough to warrant mitigation by specific commands. The mitigation was dubbed the "Song and Dance" (SAD) because the mechanism executes a series of moves designed to minimize drift of the mechanism and improve the repeatability of the OSM1 position. This move strategy has the added benefit of redistributing lubrication about the mechanism such that it was deemed unnecessary to implement a separate redistribution procedure. SAD moves are currently implemented for moves that are larger than 3 motor steps and any OSM1 movements that are against the "preferred" direction of the mechanism. The preferred direction is defined as OSM1 rotation that occurs in the order of G140L to NCM1 to G130M to G160M.


Figure 2. Schematic of the OSM1 wheel positions for COS cenwaves showing how motor steps on the OSM1 correspond to cenwaves (FP-POS = 3). The Flight Software Table contains more cenwave entries than are presently used for COS observations so some of the cenwaves shown in the figure may not be cenwaves available for GO observations. The preferred direction is such that the mechanism rotates from G140L to NCM1 to G130M to G160M. The softstops prevent the mechanism from rotating from G160M straight to G140L.

While a non-SAD move simply moves from one motor step to the commanded motor step, a SAD move involves:

1. Move to a position 200 steps lower than the desired location.
2. Move the mechanism in the preferred direction 198 steps.
3. Move the mechanism in the preferred direction 1 step.
4. Move the mechanism in the preferred direction 1 step.

For every set of COS FUV exposures there are only two types of moves: SAD moves and non-SAD moves. We show below that during COS operations the OSM1 has begun to behave differently depending on whether a SAD move is executed or not. One consequence of a SAD move is additional time due to the extra movements of the mechanism. In the Astronomer's Proposal Tool (APT), TRANS accounts for a SAD move by adding 72 seconds of overhead.

All visits start from the OSM1 "STScI home position" (also referred to as the "Central Wavelength home position"), which is set by the COS Team, and is the location on the wheel that all observations start from and stop at. This home position can be set to any COS cenwave, but recent efforts have been made to set the home position to a cenwave more commonly used for science observations in the event the OSM1 becomes stuck and can no longer move. Throughout much of the lifetime of COS the home position was set to cenwave G130M/1309, FP-POS $=3$. The home position was changed to G130M/1291, FP-POS $=3$ at the start of LP4 observations (MJD = 58028), and changed again to G130M/1222, FP-POS $=3$ at the start of LP5 observations (MJD = 59490). As explained in detail below, we found that the chosen home position has some effect on OSM1 behavior, so the home position was changed back to G130M/1291 on MJD $=59785$, with the results of that change described in detail in Debes et al. 2023. A summary of COS FUV home positions is shown in Table 1. Because COS now operates in a "hybrid" mode, utilizing multiple LPs in the same cycle depending on the cenwave, the "LP" in Table 1 refers to the date on which these LPs were first used by any cenwave.

Table 1. OSM1 Home position locations

| LP | MJD Range | OSM1 Home Position |
| :--- | :---: | :---: |
| LP1-LP3 | MJD $<58028$ | G130M/1309 |
| LP4 | $58028<$ MJD $<59490$ | G130M/1291 |
| LP5 | $59490<$ MJD $<59785$ | G130M/1222 |
| LP5 corrected | MJD $>59785$ | G130M/1291 |

## 2. Monitoring of Spectrum Placement in the Dispersion Direction

The COS calibration pipeline, CalCOS, measures the spectrum placement in the dispersion direction via a chi-squared minimization technique that determines the shift in the dispersion direction between a lamp template and the observed instantaneous wavecal spectrum obtained either from the TAGFLASH counts or a nearcontemporaneous WAVECAL exposure. The reported shifts are relative to the lamp template (generally created at the commissioning of an LP) and are in units of detector
pixels, measured as pixels away from the nominal FP-POS $=3$ position for each cenwave. These shifts can be found in calibrated COS data products, noted by the "SHIFT1A" and "SHIFT1B" keywords, indicating the shift found for each detector segment.

Because the zero-points of the lamp template spectra used in the LAMPTAB reference files (see Section 3.7.10 of the COS IHB for a full description of the LAMPTAB reference file) vary slightly from LP to LP, we apply a small offset to each SHIFT1A/SHIFT1B value to convert them to shifts measured relative to the LP1 LAMPTAB spectra at FP-POS $=3$. We refer to these shifts as "SHIFT1A ${ }_{\text {lamp" }}$ and "SHIFT1B ${ }_{\text {lamp }}$ ", defined explicity as:

SHIFT1 $\mathrm{A}_{\text {lamp }}=$ SHIFT1A + LAMPTAB shift offset
We primarily show only "SHIFT1A $\mathrm{A}_{\text {lamp" }}$ as we found that, as expected, the shift values measured for each detector are nearly identical in almost every case, i.e., the OSM1 mechanism position is measured to be at the same location on both detector segments. Table 2 shows the offsets that were applied to each SHIFT1A value at each LP for each cenwave, which were obtained by cross correlating the FP-POS $=3$ LAMPTAB spectra to the LAMPTAB spectra at LP1 FP-POS $=3$. The LAMPTAB used at LP2 is the same as LP1, so only LP3 - LP6 are shown in Table 1. Because not every cenwave is used at each LP, some entries are marked as "N/A".

Table 2. LAMPTAB shift offsets in pixels

| Cenwave | LP3 | LP4 | LP5 | LP6 |
| :--- | :---: | :---: | :---: | :---: |
| 800 | -32.33 | -32.33 | N/A | N/A |
| 1105 | 26.3 | 10.16 | N/A | N/A |
| 1280 | -2.97 | -30.36 | N/A | N/A |
| 1222 | 0.42 | -20.22 | N/A | N/A |
| 1291 | 19.9 | -7.66 | -64.07 | N/A |
| 1533 | 0.0 | 0.0 | N/A | 0.0 |
| 1577 | 25.67 | 8.8 | N/A | -20.91 |
| 1589 | 36.77 | 5.77 | N/A | -15.88 |
| 1600 | 40.9 | 11.79 | N/A | -11.8 |
| 1611 | 38.35 | 9.04 | N/A | -13.75 |
| 1623 | 40.22 | 12.35 | N/A | -3.51 |

The instrument also measures the OSM1 position using a fine and coarse resolver. These resolvers, when combined, have a resolution of $\sim 1 / 5$ of an FP-POS step ( $\sim 50$ pixels), so they are less precise than the SHIFT1A ${ }_{\text {lamp }}$ values discussed above, but should correlate with the SHIFT1 $\mathrm{A}_{\text {lamp }}$ values. We combine the reported fine and coarse resolve location into a quantity we refer to as the "Resolver Position", which is a combination of the fine ("LOM1POSF", 8 bit) and coarse ("LOM1POSC", 16 bit) resolvers, and is calculated using the following equation:

Resolver Position (degrees) $=\left(\frac{\text { coarse }}{2^{16}}\right) * 360+\frac{1}{1066 . \overline{66}} *\left[\left(\frac{\text { fine }}{2^{8}}\right) * 360\right]$

The factor of $1 / 1066.66$ is required as the coarse resolver measures the location of the stepper motor and the fine resolver measures the location of the optics wheel, which are coupled with a gear ratio of 1066.66 as described above and in the COS SE02 (Osborne 2004).

Figure 3 shows that the Resolver Position is well-correlated with the SHIFT1A $A_{\text {lamp }}$ values, verifying that the SHIFT1A ${ }_{\text {lamp }}$ values can indeed be interpreted as physical positions on the OSM1. We also performed an additional check of measuring the location of Ly $\alpha$ on the detector and verifying that the position of this emission line is well-correlated with the position as indicated by the SHIFT1A ${ }_{\text {lamp }}$ values. Therefore, throughout this analysis we use the SHIFT1 $\mathrm{A}_{\text {lamp }}$ values to describe the physical motor step position of the OSM1.


Figure 3. Plots of the SHIFT1A ${ }_{\text {lamp }}$ positions as measured by the COS calibration pipeline (CalCOS) vs. the measured position according to the OSM1 fine and coarse resolvers for cenwave 1291 (left) and cenwave 1222 (right). Points are colored by the motor step (FP-POS) at which they were observed. Because the SHIFT1A ${ }_{\text {lamp }}$ values are well-correlated with resolver position, the SHIFT1 $\mathrm{A}_{\text {lamp }}$ values can be interpreted as measurements of the physical motor position on the OSM1.

## 3. Anomalous Spectral Placements in the Dispersion direction

In this section, we describe the anomalous spectral placements in the dispersion direction that were found for the G130M/1291 and G130M/1222 observing modes, and explain how they correlate with OSM1 movements and affect COS science observations. In Section 3.1, we first show the anomalous spectra placement of G130M/1291, which started occurring at the onset of LP4 operations (on or about October 2, 2017). Then, In Section 3.2, we describe how the dispersion direction placement of a spectrum is correlated with the type of OSM1 motion that occurred before the spectrum was taken. In Section 3.3 we examine how the anomalous spectral placement for G130M/1291 affects long-term gain sag. We present the anomalous spectral placement for G130M/1222 in Section 3.4, as well as show other modes that show similar shift behavior to G130M/1222. Finally, in Section 3.5, we discuss potential impacts of the anomalous and imprecise spectral placement on science data.

### 3.1 Anomalous spectral placement for G130M/1291

Figure 4 shows the SHIFT1A lamp $^{\text {values as a function of MJD for each FP-POS of all }}$ G130M/1291 observations. The left panel shows SHIFT1A ${ }_{\text {lamp }}$ values across all 4 FPPOSs from the time COS was installed through October 2022, and the right panel shows only FP-POS $=4$ for a more restricted time range (starting just before LP4 operations began). Dashed vertical lines indicate instances where the home position of the OSM1 mechanism changed, as mentioned in Section 1.3 above, and the lime-green dotted lines indicate the required accuracy of $+/-1 / 2$ FP-POS from the median LP1 and LP2 placements. COS 2025 rules, described in detail in Oliveira et al. 2018, were implemented at the start of LP4 operations (MJD = 58028), restricting the use of cenwave 1291 to just FP-POS $=3$ and FP-POS $=4$ to mitigtate gain sag due to Ly $\alpha$ airglow. Before the start of LP4 operations, the scatter in the position of spectrum placement at each FP-POS was quite low ( $\sigma=17$ pixels for FP-POS $=3$ and $\sigma=22$ pixels for FP-POS = 4), with no obvious trends with time. However, beginning at MJD $=58028$ (October 2, 2017), we found that the scatter in the SHIFT1 A ${ }_{\text {lamp }}$ values increased to $\sigma=25$ pixels for FP-POS $=3$ and $\sigma=49$ pixels for FP-POS $=4$ during LP4 operations, and the SHIFT1A lamp values shifted by $\sim 100$ pixels for FP-POS $=4$. The scatter was even higher for LP5 operations ( $59490<$ MJD $<59785$, or Oct 2021 Jul 2022), with standard deviations of $\sigma=48$ and $\sigma=79$ pixels for FP-POS $=3$ and FP-POS $=4$, respectively.


Figure 4. Left: SHIFT1A ${ }_{\text {lamp }}$ positions vs. time for G130M/1291 for each FP-POS. Right: Same as left, but only showing $\mathrm{FP}-\mathrm{POS}=4$, and for a more restricted time range. Vertical dashed lines indicate instances of a change in home position of the OSM1, which correspond to changes from LP3 to LP4 operations (MJD $=58028$, left-most vertical line) and LP4 to LP5 operations (MJD $=59490$, right-most dashed vertical line). The dotted vertical line at recent times (MJD = 59785) marks when the COS Team changed the home position back to the home position previously used during LP4 operations (c1291). The horizontal lime green lines on each panel indicate $+/-1 / 2$ FPPOS distance from the median SHIFT1 $\mathrm{A}_{\text {lamp }}$ position at LPs 1-2.

As shown in the right panel of Figure 4, the increase in scatter is partly due to an apparent bimodality in the SHIFT1 $\mathrm{A}_{\text {lamp }}$ distribution, which is strongest in the FP-POS $=4$ SHIFT1A $A_{\text {lamp }}$ values. The bimodailty is such that the low locus of SHIFT1A lamp values at FP-POS $=4$ are at the same value as they were for previous LPs (SHIFT1 Alamp $\sim 250$ pixels), whereas the new behavior beginning at LP4 is an increase in some of the FP-POS $=4$ SHIFT1 $A_{\text {lamp }}$ values (SHIFT1 $A_{\text {lamp }} \sim 350+$ pixels). This behavior continued at the start of LP5 operations (MJD = 59490), with signs of even larger scatter for FP$\operatorname{POS}=3$, and a change in the temporal trends at $\mathrm{FP}-\mathrm{POS}=4$.

### 3.2 Small (non-SAD) vs. Large (SAD) moves

In Section 1.3 we described the series of moves that takes place when the OSM1 moves from a position that is larger than 3 motor steps away from its present position, referred to as the "Song and Dance" (SAD). Smaller moves, such as moving from one FP-POS to the next, do not move with SAD (non-SAD). To analyze the extent to which the 1291 FP-POS $=3$ and FP-POS $=4$ SHIFT1 $A_{\text {lamp }}$ values presented above are correlated with the type of move that preceded the exposure, we plot in Figure 5 the difference in SHIFT1 $A_{\text {lamp }}$ values between what they were after LP4 operations began and what they were at LP1. We separate these quantities based on what OSM1 movement occurred before any given exposure. We do this for 3 separate time periods, "LP4 early" (58028 < MJD < 58750), "LP4 late" (58750 < MJD < 59490), and LP5 (59490 < MJD < 59900).


Figure 5. Histograms of $1291 \mathrm{FP}-\mathrm{POS}=3$ and $\mathrm{FP}-\mathrm{POS}=4$ SHIFT1A $_{\text {lamp }}$ values measured relative to the median FP-POS $=3$ and FP-POS $=4$ SHIFT1 $A_{\text {lamp }}$ values at LP1. The distributions are colored by the type of preceding OSM1 move that brought the OSM1 to the FP-POS $=3$ or FP-POS $=4$ position, as indicated in the legend (red corresponds to a "SAD" move and blue and green correspond to "non-SAD" moves). Each panel shows a different time period, with the far left corresponding to "LP4 early" (58028 < MJD < 58750), "LP4 late" (58750 < MJD < 59490), and LP5 (59490 < MJD $<59900$ ).

The distribution shown in red in Figure 5 demonstrates that large moves (e.g., moves from an NUV Image Acq) to an FP-POS will result in a SHIFT1A $A_{\text {lamp }}$ value that was similar to the SHIFT1A ${ }_{\text {lamp }}$ values at LP1, with a small scatter of $\sim 26$ pixels. However, smaller moves that operate in non-SAD, primarily included in the green distribution of Figure 5, are $\sim 120$ pixels off from where they were at LP1, with a larger scatter of $\sim 40$ pixels. This distribution shifts to larger SHIFT1 $A_{\text {lamp }}$ values with increasing time and the scatter increases to $\sim 50$ pixels for observations taken during LP5 operations.

The exposures taken after a spectroscopic Acq, which are generally SAD moves that are smaller than SAD moves from the NUV (blue), show a SHIFT1A ${ }_{\text {lamp }}$ disribution that is between the NUV SAD (red) and non-SAD (green). These exposures tend to be at larger SHIFT1A $A_{\text {lamp }}$ values during LP5 operations than they were at LP4. To summarize, a large SAD move still results in a precise spectrum placement for G130M/1291 ( $\sigma \sim 20$ pixels), but a small non-SAD move is less precise ( $\sigma>40$ pixels).

### 3.3 Long-term Gain-sag consequences

The COS Team closely monitors the modal gain of COS FUV, and makes various policy decisions (e.g., raise detector high voltage) to prevent gain sag from negatively impacting COS FUV data (see e.g., Johnson et al. 2023 for an in-depth discussion on gain sag at LP5 and LP6). Upon discovering the correlation between type of move and resulting SHIFT1 $\mathrm{A}_{\text {lamp }}$ value, the COS team implemented a new policy that avoided observations consisting of an NUV target Acq followed immediately by an exposure at $\mathrm{FP}-\mathrm{POS}=4$. The motivation for doing this was to avoid growing a second gain-sag hole at the FP-POS $=4$ position. Figure 6 shows that by the time we implemented this rule (October 2022), the gain-sagged region due to SAD moves to $1291 \mathrm{FP}-\mathrm{POS}=4$ (XCORR ~ 9350) had not yet sagged enough to become a gain sag hole (modal gain below 3), but the non-SAD move positions (XCORR $\sim 9500$ ) were just becoming a gain-sag hole.

We also conducted a series of simulations to see how the gain would sag over time if we required all SAD moves for $\mathrm{FP}-\mathrm{POS}=4$. The top panel of Figure 6 shows that inside of 4 months from October 2022, disabling the SAD moves to FP-POS $=4$ (blue line in Figure 6) results in a slower growth of the left-most FP-POS = 4 hole (XCORR~9350), creating a longer time over which we have only 2 gain-sag holes instead of 3. Had we forced all SAD moves to $\mathrm{FP}-\mathrm{POS}=4$, we would have quickly burned one large gain sag hole at this region (red curve). However, the bottom panel shows that, by October 2023, either scenario will result in gain sag in both FP-POS $=4$ holes such that we end up with one large hole from $\sim 9000$ to 9600 pixels in XCORR (approximately $\sim 10 \AA$ in wavelength). As demonstrated in Hasselquist et al. in prep, observing with 3 or more FP-POSs at LP6, which is close enough to LP5 to be affected by these gain sag holes, will still result in successfully dithering over this large gain sag hole, resulting in continous spectral coverage. To avoid growing a large hole early at the FP-POS $=4$ position at future LPs, the COS Team could revisit forcing SAD moves for 1291 to grow deep, but narrower holes.


Figure 6. Gain map traces (modal gain vs. XCORR for fixed YCORR location, shown in black) and simulated gain traces (shown in red and blue) at the Ly $\boldsymbol{\alpha}$ region of FUVB for the LP5 cross-dispersion location. The top panel shows the expected gain sag 4 months after October 2022, and the bottom panel shows the expected gain sag 12 months after October 2022. The simulated traces show what the predicted modal gain would be if we force all moves to FP-POS $=4$ to be SAD (red) and if we force all moves to FP-POS $=4$ to be non-SAD (blue). The horizontal dashed line indicates a modal gain of 3, at and below which defines a gain sag hole. The vertical lime green dashed lines indicate the approximate XCORR locations of the centers of the gain sag holes.

### 3.4 Small moves shifting in 1222 and G140L

The temporal trends in the SHIFT1A $\mathrm{lamp}_{\text {lam }}$ values are not limited to G130M cenwave 1291. Figure 7 shows how the SHIFT1A $\mathrm{l}_{\text {lamp }}$ values change with time for G130M/1222. Similar to 1291, the scatter in SHIFT1 $A_{\text {lamp }}$ values at each FP-POS appears to increase with the onset of LP4 operations, beginning at MJD $=58028$. However, there is a dramatic shift in the SHIFT1 A ${ }_{\text {lamp }}$ values beginning at LP5 operations (MJD > 59490). The right panel of Figure 7 shows FP-POS $=4$ only for 1222, with a time period beginning shortly after the onset of LP4 operations. There is a steep trend of increasing SHIFT1 $A_{\text {lamp }}$ value with time at a rate of $\sim 0.5$ pixels/day beginning at MJD $>59490$. This trend may have been flattening out during the time period of $59700<$ MJD $<$ 59800, but there were too few 1222 COS exposures during this time period to conclude that the SHIFT1 $\mathrm{A}_{\text {lamp }}$ values were actually flattening.


Figure 7. Same as Figure 4, but for G130M/1222.
Because 1222 remained at LP4 when LP5 operations began (only c1291 moved to LP5), it was suggested that changing the OSM1 home position is responsible for inducing this behavior in 1222. As explained in more detail in Debes et al. 2023, we developed and executed a special calibration program that monitored the 1222 OSM1 placement after changing home position back to 1291 from 1222. These are the points in Figure 7 that are farther to the right than the dotted line (MJD > 59785), and show that the change in home position resulted in the SHIFT1 $A_{\text {lamp }}$ values going back towards where they were at LP4.

We find similar behavior occurred for G140L, as shown in Figure 8. The trends in FPPOS $=2$ and 4 for G140L/1105 were not as steep as G130M/1222, but we still observe an increase beginning at LP4 operations (G140L cenwaves remained at LP3) followed by an apparent flattening ~halfway through LP4 operations. These correlations in change in the SHIFT1A lamp values with time suggest that they are also caused by the OSM1 home position changes.

We do not observe the same temporal change in SHIFT1 $A_{\text {lamp }}$ values for G160M. Most G160M cenwaves show flat trends with time, with the notable exception being 1577 (shown in Figure 9). However, this cenwave shows an increasing trend in SHIFT1 A ${ }_{\text {lamp }}$ values at FP-POS $=2$ and FP-POS $=4$ from the start of LP3 operations to the present day, without an obvious change in behvaior at the onset of LP4 operations. The right panel of Figure 9 shows that roughly halfway through LP4 operations, the increasing trend stopped and decreased slightly, potentially continuing this downward trend into LP5 operations.


Figure 8. Same as Figure 4, but for G140L/1105.


Figure 9. Same as Figure 4, but for G160M/1577.

We summarize the behavior of each COS FUV cenwave by calculating a standard deviation of SHIFT1 $A_{l a m p}$ values across the lifetime of each cenwave in Table 2. We visually inspected all plots similar to Figures 7-9 and find no additional temporal trends of note. Not every cenwave shown in Table 2 was used for the entire lifetime of COS, so the standard deviations are calculated over shorter time periods for some cenwaves.

Table 3. Standard deviations of the SHIFT1 $\mathrm{A}_{\text {lamp }}$ values in units of pixels for all COS cenwaves across the entire cenwave lifetime.

| Cenwave | FP-POS = 1 | FP-POS = 2 | FP-POS = 3 | FP-POS = 4 |
| :--- | :---: | :---: | :---: | :---: |
| 800 | 9.3 | 13.6 | 10.7 | 13.2 |
| 1105 | 13.4 | 19.1 | 16.0 | 16.4 |
| 1280 | 14.1 | 14.2 | 14.8 | 14.2 |
| 1222 | 14.7 | 23.7 | 24.5 | 23.8 |
| 1291 | 11.7 | 21.8 | 17.5 | 93.9 |
| 1533 | 8.1 | 14.4 | 22.6 | 18.7 |
| 1577 | 13.3 | 28.0 | 29.2 | 35.5 |
| 1589 | 17.2 | 31.5 | 19.1 | 19.6 |
| 1600 | 9.8 | 24.5 | 21.6 | 26.0 |
| 1611 | 10.7 | 21.9 | 20.0 | 18.0 |
| 1623 | 19.3 | 27.0 | 17.7 | 31.3 |

### 3.5 Science Impacts from Imprecise Spectral Placements

For most COS science applications, the impact of imprecise spectral placements are small. We looked at the OSM drift across the duration of the full length of these exposures and found that the drift in the imprecise spectral placement exposures is typical of that characterized in James et al. (2023). Therefore, the calibration pipeline is able to return as accurate and precise wavelength calibrations as it was able to before the increase in scatter of spectral placement occurred. On the other hand, the wavelength coverage for any given FP-POS $=4 \mathrm{G130M} / 1291$ exposure can vary by up to $\sim 4 \AA$, so users interested in a spectral feature that shows up at the edges of FP-POS $=41291$ exposures might want to consider forcing a SAD move to this exposure. Similarly, users who are interested in variability studies, such as transiting exoplanets, might want to choose OSM1 movements that include a SAD move to ensure that subsequent exposures at a given FP-POS lie on nearly the same location of the detector.

As mentioned in Section 2, there is an effect on the long-term gain sag of the detector. Specifically, the gain sag holes at LP4 and LP5 will be slightly larger than what they were in previous LPs. This ends up affecting the spectral coverage of LP6. As detailed more in Hasselquist et al. in prep, if fewer than 4 FP-POSs are used at LP6 to mitigate overheads, FP-POS = 1+4 will not successfully dither across these large gain-sag holes as they can overlap with a very low response region resulting in a hole of size $\sim 0.3 \AA$. However, including a third FP-POS will result in continuous spectral coverage.

## 4. Physical explanation for anomalous spectral placements in the dispersion direction

The OSM1 assembly relies on both friction and magnetic forces within the stepper motor to arrive at a particular commanded step position. Telemetry and measurements of the SHIFT1 keywords show that the repeatability of OSM1 has evolved over time, especially for non-SAD moves, both in absolute detector location for a given commanded position and in repeatability of placement. The COS team considered several scenarios that might have accounted for these changes. Any physical explanation should account for both systemic trending in spectrum placement as well as the growing separation between SAD and non-SAD moves.

The mean placement of a spectrum corresponds to how well the stepper motor is stopping relative to the commanded position as defined by the location at early times in instrument operations. If we assume that the magnetic forces present in the motor are not significantly changing with time, this leaves the issue of friction due to changes in lubrication as the remaining physical cause for the observed behavior. If the spectrum has a larger positive SHIFT1 $A_{\text {lamp }}$ value than the mean position, there was less friction in the stopping, whereas if the spectrum has a negative SHIFT1A $A_{\text {lamp }}$ value relative to the mean position there was more friction. Thus, over time both the G130M/1291 and G130M/1222 stopping positions are experiencing less friction, with potentially a greater variability in friction conditions when a non-SAD move is executed. The same issue does not seem to be present when SAD moves are used, which is evident at both FP-POS=3 and 4 for G130M/1291. For G130M/1222, only FP-POS = 1 typically comes from a SAD move, which shows less variabilitiy in position with time as compared to the other FP-POSs.

Several possible explanations were explored by the COS team for these changes in friction, such as HST safings and changes in usage due to COS 2025 rules. Neither of these possibilities were well correlated in time with the behavior seen in the SHIFT1A lamp monitoring. The biggest correlation in behavior was associated with changes to the home position, but changing the home position apparently only affects the temporal trends from small moves, and seems to have no obvious influence on why these moves became less precise in the first place. While investigating the exact causes of the SAD vs. non-SAD OSM1 move precision and apparent move offsets are beyond the scope of this work, we have discovered some additional behavior and correlations that might aid future investigations. As described in detail in the Appendix, we show that after COS 2025 rules were implemented at the beginning of LP4 operations, the distance between FP-POS $=3$ to FP-POS $=4$ for G130M/1291 went from $\sim 275$ pixels to 375 pixels, potentially indiciating a change in the lubrication distribution causing some of the observed OSM1 behavior. We also find that other telemetry data, such as aperture mechanism position and OSM1 focus motor location, are partially correlated with SAD vs. non-SAD moves. It is not apparent why these correlations exist, but the existence of these correlations suggest future investigations into the causes of the observed behaviors should start by understanding all commanded mechanism movements (OSM1 and other mechanisms) that occur throughout the course of an observation.

## 5. Summary

We present temporal trends of the OSM1 that are responsible for placing the COS FUV spectrum at a specific location in the dispersion direction. We find that, beginning at LP4 operations, the smaller OSM1 motions for G130M/1291 that occur without the song and dance (SAD) became less precise, and generally resulted in OSM1 spectra placements that were farther apart from FP-POS $=3$ ( $>270$ pixels and up to 450 pixels) than they were during LP3 operations and before. OSM1 movement to FP-POS = 3 and FP-POS $=4$ that occurred with a SAD move are as precise as they ever were. This behavior results in a slightly larger gain-sag hole at LP4 and LP5 than expected based on hole size and location at previous LPs, and results in spectral placement that is less repeatable than at previous LPs. The cause of this imprecise spectral placement for small moves is unknown at this time.

We also find temporal trends in the OSM1 placement that are clearly correlated with home position moves. As explained more in Debes et al. 2023, moving the OSM1 home position back to 1291 from 1222 reversed a problematic increasing trend in the G130M/1222 SHIFT1A $A_{\text {lamp }}$ values and decreased some of the increased scatter of the G130M/1291 SHIFT1 $A_{\text {lamp }}$ values. We theorize the cause of this behavior to be related to the redistribution of lubricant about the mechanism that occurs in the moves following a home position change. Such lubrication distribution might be related to what is causing the non-SAD moves at G130M to be less precise, but doesn't fully explain why the SAD moves are nearly as precise as they were in the past. Temperature of the OSM1 motor could also be a factor, and is briefly described in Debes et al. 2023.

These behaviors have minimal effects on COS science, but users who are concerned about wavelength regions at the edge of the detectors, or who are worried about repeat observations falling on the exact same part of the detector should consider structuring their observations such that they use SAD for all OSM1 moves.

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## Appendix

Here we provide some additional details of how exactly the FP-POS $=3$ to FP-POS $=4$ moved changed at the beginning of LP4 operations for G130M/1291, as well as some other correlations that were found when investigating the cause of the change in OSM1 behavior.

While the SHIFT1A lamp distributions for the SAD vs. non-SAD moves for G130M/1291 may not be entirely explained by the OSM1 home position move, we do find a few correlations that might point to an answer for future investigations. Figure 10 shows the difference in SHIFT1A ${ }_{\text {lamp }}$ values when moving from FP-POS $=3$ to FPPOS $=4$ for G130M/1291 observations starting from LP3 until recent times, i.e., how far the OSM1 moved (when converted to equivalent pixels) to get to the FP-POS $=4$ position. Points are colored according to the type of move that ocurred before the FPPOS $=3$ exposure. For LP3, when the OSM1 almost always moved from FP-POS = 2 to FP-POS $=3$, the OSM1 moved a consistent $\sim 275$ pixels. However, once COS 2025 rules were implemented for LP4, the OSM1 moved farther. For LP5 observations, if the OSM1 moved to the FP-POS $=3$ position from a ACQ/PEAKD, then there were instances where the OSM1 moved only 200-250 pixels to get to FP-POS $=4$ instead of the 250-400 pixels that were moved at LP4.

To highlight these correlations, we show in Figure 11 the SHIFT1 $A_{\text {lamp }}$ values for the FP-POS $=3$ exposure plotted against the SHIFT1 $\mathrm{A}_{\text {lamp }}$ values for the subsequent FPPOS $=4$ exposure, again colored according to the type of exposure that preceded the FP-POS = 3 exposure. We do this for the same time periods defined in Secion 3.2: "LP4 early", "LP4 late", and LP5. Figure 11 shows that the correlation of FP-POS $=3$ and FP-POS $=4$ shift values for the exposure sequences starting with an NUV Acq (blue points) changed during the "LP4 late" period, with the resulting FP-POS $=4$ shift values becoming much more tightly correlated with the previous FP-POS $=3$ shift values. We also find that the subsequent FP-POS $=3$ and FP-POS $=4$ shift values for exposure sequences beginning with a ACQ/PEAKD became slightly anti-correlated in LP5 for the exposures that start with an FP-POS $=3$. The fact that these changes in correlations occurred when the COS2025 rules were implemented could suggest that a redistribution of lubricant resulted in a larger FP-POS $=3$ to FP-POS $=4$ move.


Figure 10. Difference in SHIFT1 $A_{\text {lamp }}$ values between FP-POS $=3$ and FP-POS $=4$ plotted as a function of time for G130M/1291 observations beginning around LP3 operations. Points are colored according to the type of exposure preceding the FP-POS $=3$ observation, with exposures that are $>3$ exposures into a sequence colored in red. The y-axis essentially shows how far the OSM1 moved during the FP-POS $=3$ to FPPOS $=4$ move .


Figure 11. SHIFT1 $A_{\text {lamp }}$ values for the FP-POS $=3$ exposure plotted against the SHIFT1A ${ }_{\text {lamp }}$ values of the subsequent FP-POS $=4$ exposure divided into the same time bins as Figure 5. Points are colored as in Figure 10.

We also noticed a few additional correlations between OSM1 behavior and various other telemetry data that might be useful for future follow-up investgations. Figure 12 shows that after the start of LP5 (bottom row), the telemetry data from the FP-POS $=4$ exposure is different based on whether the observing sequence was NUV Acq $->$ FPPOS = 3 -> FP-POS $=4$ (blue) or ACQ/PEAKD/XD -> FP-POS = $3->$ FP-POS =4 (green). Specifically, the telemetry reports a different aperture mechanism Y position (both commanded and reported) and OSM1 focus motor location. While optically these differences should not explain the differences in spectrum placement, theses differences do suggest that more than just the OSM1 wheel is changing when the observations occur. Future investigations of the causes of the SAD vs. non-SAD OSM1 move precision/offset may want to first consider understanding all commanded mechanism movements (OSM1 and other mechanisms) that occur throughout the course of an observation.


Figure 12. Left column: the reported commanded aperture block position for LP3 (top row), LP4 (middle row), and LP5 (bottom row), with points colored according to the move that preceded the observation. The middle and right column are similar, but show aperture resolver position and OSM1 focus motor resolver position, respectively. Note that the plotting scales are different for each panel.

