Characterization of the COS FUV Detectors

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\textbf{ABSTRACT}

This document describes the results derived from the COS calibration Program 12676, “COS/FUV Characterization of Detector Effects”. This program surveyed the COS FUV detectors in order to determine the best locations for future science operations. Specifically, these data were used to: 1) derive on orbit bad pixel maps over the accessible region of the FUV detectors, and; 2) derive gain maps which are used to model the expected lifetime of different detector locations.

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1. Introduction

This document describes the results derived from the COS calibration Program 12676, “COS/FUV Characterization of Detector Effects”. This program was one of three programs that explored the FUV detectors for the purpose of selecting a new lifetime position. Program 12676 surveyed the COS FUV detectors in order to assess their flaws and gain properties in order to determine the best locations for future science operations. The deuterium lamp was used because it only required internal orbits and because it fills the Flat Field Calibration Aperture (FCA), requiring fewer cross-dispersion locations than an external target. The data from this program were used to produce two specific data products:

1. 2-D images of the COS FUV detectors over the range accessible to the deuterium lamp.
2. 2-D gain maps over the area of each detector exposed to the deuterium lamp.

These products were then used for the following analyses:

1. The images were used to determine the locations of low response and dead detector regions to produce updated bad pixels tables.
2. The gain maps were used to create a model to determine the optimal locations of future lifetime positions and to predict (based on previous usage) how long the new lifetime positions will last before gain sag becomes so severe that either an increase in the high voltage (HV) or a move to another, unused, location is required.

The results of this analysis, together with spectral resolution considerations, were used to determine the locations of subsequent lifetime positions (see Oliveira et al. 2013).

2. Observations

We exposed the active area which can be used for science (and accessed by the deuterium lamp) to the deuterium lamp through the FCA. This required moving the FCA in Y\footnote{Unless stated otherwise, the X and Y coordinates used in this document refer to the walk corrected XCORR and YCORR fields of a standard COS CORRTAG file.} to locations that will expose as much of the detectors as possible. Because the spectral energy distribution (SED) of the deuterium lamp becomes very weak short ward of ~ 1250Å and long ward of ~ 1650Å, it was necessary to use the G130M grating for segment A and the G160M grating for segment B to produce uniform counts over each segment.
2.1 Exposure Times

One potential use of the data was to extract simulated PSA 1-D flat fields from the data. PSA spectra can have FWHMs as narrow as 10 Y pixels. Experience has shown that a S/N \( \simeq 10 \) per collapsed pixel in the spectral direction for each FPPOS observation is required to extract good quality 1-D flats using the FPPOS algorithm (see Ely et al. 2011). Thus, the criterion adopted was to obtain at least 10 counts/pixel (or 100 for a collapsed pixel) at each FPPOS setting. This is equivalent to 40 counts/pixel when the data from all four FPPOS settings are summed for a region that does not overlap with data from observations obtained at an adjoining Y location. The exposure times required to accomplish this were determined by scaling previous deuterium lamp exposures obtained during SMOV (programs 11483 and 11488). The expected count rates were assumed to be 15% less due to the time dependence of the detector sensitivity since SMOV (deuterium lamp fading also needs to be considered, see below). The SMOV data have minimum count rates of about 0.015 cnts/s/pixel, or 0.15 cnts/s over a 10 pixel slit. To obtain a S/N = 10 requires an exposure time of 100/0.15 = 666 sec, and allowing for a 15% reduction in count rate gives 784 s. Thus, the individual exposures were set to 900 s to provide a comfortable margin of error and to allow for a possible 15% fading of the deuterium lamp due to use throughout the program.

2.2 Positioning the spectra

Placing the spectrum at the desired detector location is somewhat complicated, so we describe it here in some detail.

Let \( Y \) = the geometrically corrected cross-dispersion detector coordinate (YCORR), and define:

\[
\begin{align*}
Y_0 & = \text{Centroid range (depending on grating) of a spectrum at its default position.} \\
Y_c & = \text{Centroid position at a given XAPER value.} \\
\Delta Y & = Y_c - Y_0 \\
Y_{a1}, Y_{a2} & = \text{Minimum and maximum Y values for active area.} \\
XAPER & = \text{APT parameter used to position the aperture.} \\
LAPXSTP & = \text{Parameter used by the telescope to set the aperture location, restricted to } \pm 275 \text{ by the on board soft stops.} \\
XAPER_0 & = \text{LAPXSTP value for XAPER = 0 (aperture dependent).}
\end{align*}
\]

For the initial lifetime settings:

<table>
<thead>
<tr>
<th></th>
<th>( Y_0 )</th>
<th>( XAPER_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUVA</td>
<td>( Y_{a1} ) = 310, ( Y_{a2} ) = 730</td>
<td>PSA = 475–495, FCA = 484, FCA = -153.1, PSA = 126.1</td>
</tr>
<tr>
<td>FUVB</td>
<td>( Y_{a1} ) = 370, ( Y_{a2} ) = 780</td>
<td>PSA = 530–550, FCA = 540, FCA = -153.1, PSA = 126.1</td>
</tr>
</tbody>
</table>
where the range in PSA $Y_0$ values is for the G130M and G160M (the FCA is filled aperture, so there is no grating dependence). Since each $Y$ pixel is $\approx 0.1''$ and 21 XAPER steps is $\approx 1''$ in the opposite direction, the position of the spectrum centroid for a given XAPER value is:

$$XAPER \approx -2.1 (Y_c - Y_0) \equiv -2.1 \Delta Y$$

The relation between LAPXSTP and XAPER is

$$LAPXSTP = XAPER + XAPER_0 = XAPER_0 - 2.1 \Delta Y$$

which gives

$$\Delta Y = -(LAPXSTP - XAPER_0)/2.1$$

The $\Delta Y$ corresponding to the LAPXSTP= $\pm$275 soft stops are $-203.9 \leq \Delta Y \leq +58.0$ and $-70.9 \leq \Delta Y \leq 191.0$ for the FCA and PSA, respectively. These translate into the $Y$ ranges for the different apertures and segments given in the table.

<table>
<thead>
<tr>
<th></th>
<th>FCA</th>
<th>PSA</th>
<th>Overlap</th>
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<tr>
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<td>404 $\leq Y \leq 686$</td>
<td>404 $\leq Y \leq 542$</td>
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<tr>
<td>FUVB</td>
<td>336 $\leq Y \leq 598$</td>
<td>459 $\leq Y \leq 741$</td>
<td>459 $\leq Y \leq 598$</td>
</tr>
</tbody>
</table>

When LAPXSTP = 0 for the PSA, $Y_c[\text{FUVA, FUVB}] = [544, 598]$, which roughly equals the $-275$ FCA soft stop. Larger LAPXSTP go to smaller $Y_c$, so the upper LAPXSTP position is set by the $+275$ PSA soft stop at $Y_c[\text{FUVA, FUVB}] = [404, 459]$. Thus, the values of XAPER used for the FCA are in the range $-122 \leq XAPER \leq 153$. Specifically,

$$LAPXSTP = -0.1, -55.1, -109.1, -164.1, -218.1, -268.1$$

$$XAPER = 153, 98, 44, -11, -65, -115$$

$$\text{offsets} \approx -7.3, -4.7, -2.1, +0.5, +3.1, +5.5''$$

Due to imprecision in the aperture mechanism, the translation commanded value of XAPER does not always result in exactly the expected value of LAPXSTP, but is typically within a few units.

### 2.3 Notes on special commands

To execute this program, several special commands (S/C) had to be used in the APT. The special command ELAPERSET along with QUESIPARM APERTURE FCA and QUESIPARM DET FUV that preceded every XAPER command set the value for the aperture location as the default location for the FCA so that the subsequent XAPER command moves from the appropriate location.
Then each subsequent exposure contains a special command instruction ELNOAP-MAIN, which kept the instrument from returning to the default location after each exposure.

Finally, the G160M observations (numbers 7 – 12) began with a set of commands that changed the HV setting on FUVB to the low (initial level of 167 steps). The FUVB voltage of the G130M observations were obtained at the higher voltage level (175 steps), adopted to alleviate the low gain regions that result from exposure to Ly α airglow.

2.4 Data quality

Table 1 lists the exposures obtained during the program. The data are grouped by grating. The G130M exposures were primarily used to characterize the FUV A and the G160M the FUVB. For each set, we list the file base name, the LAPXSTP parameter, which determines the $Y$ offset, the FPPOS and the exposure time. At the time this program was executed, the nominal FUVB HV had been raised to 175 steps. Therefore, the FUVB HV was lowered to 167 steps for the G160M exposures (which provide the best coverage of the FUVB). However, the higher (175 steps) HV setting for the FUVB was maintained for the G130M observations. This strategy allowed us to investigate how changes in the HV setting affect the detector gain for regions of the detector which received adequate counts with both gratings.

Figure 1 shows the deuterium spectrum over the entire range of the G130M CENWAVE = 1309 and G160M CENWAVE = 1600 for both detector segments at the LAPXSTP = $-109.1$ Y position. The individual spectra are totals of $Y$ pixels within ±40 pixels of their mean centroids. The iterative FPPOS algorithm was applied to the individual FPPOS spectra for each grating and segment to produce a single spectrum, and these were roughly aligned by eye to produce a single estimate of the entire deuterium spectrum viewed through the FCA. Black curves are for the FUVB segments, red for the FUV A (there are gaps between the segments and the G130M are to the left of the G160M). The overlap regions do not agree exactly since the two gratings have different dispersions and viewing angles and the two segments have slightly different sensitivities. Nevertheless, the figure provides a rough spectrum over the region $1155 \lesssim \lambda \lesssim 1775 \text{Å}$ and shows why the G130M FUV A and G160M FUVB provide the most uniform exposures.

The final data quality is summarized in Figure 2 for the G130M FUVA and Figure 3 for the G160M FUVB. These figures show the mean counts per pixel in the $Y$ and $X$ directions from the sum of all of the observations. In the $Y$ plots, the contributions from the four FPPOS observations at each $Y$ location are also shown along with the total. Two things in these figures are notable. First, the typical S/N per pixel is 7 – 10. Second, the spectra taken at the smallest $Y$ position were severely vignetted by the FCA aperture.
Figure 1. Total deuterium spectrum at LAPXSTP = −109.1. Black spectra are for the FUVB, red spectra for the FUVA and the G130M data are on the left. The spectra are plotted against concatenated pixels, and cover the range 1155 ≲ λ ≲ 1775Å.
Figure 2. Mean $Y$ (top) and $X$ (bottom) counts/pixel for the summed FUVA G130M deuterium data. The $Y$ mean is for counts detected in the range $2000 \leq X \leq 14000$, and $X$ mean is for counts in the range $420 \leq Y \leq 555$. For the different $Y$ locations, the contributions at each LAPXSTP setting are also shown as dashed curves.
Figure 3. Mean Y (top) and X (bottom) counts/pixel for the summed FUVB G160M deuterium data. The Y mean is for counts detected in the range $2000 \leq X \leq 14000$, and X mean is for counts in the range $470 \leq Y \leq 605$. For the different Y locations, the contributions at each LAPXSTP setting are also shown as dashed curves.
### Table 1. Exposures

<table>
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<th>File</th>
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<th>T Exp</th>
<th>File</th>
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</table>

### 3. Data Reduction

To attain the goals of this program, a 2-D flat field and a 2-D gain sag map are required. This section addresses the construction of these data products.

#### 3.1 Producing a combined flat

Determining a precise 2-D image of the detector response would require an enormous effort. One would need an exact model of both the $X$ and $Y$ walk, to understand all localized distortions and be able to characterize how the deuterium spectrum varies across the FCA and with FCA $Y$ location. Instead, an approximate representation of the detector, which was adequate for our purposes, was produced as follows:
1. All of the deuterium images were summed. Because at each Y location, there are 4 FPPOS exposures, the mean spectra should be similar. As shown in Figures 2 and 3, the mean S/N per pixel is between 7 - 10 over 130 ∼ Y pixels.

2. A mean spectrum was determined from the image and each row of the summed image was divided by it to remove the spectral signature of the deuterium lamp. The summed spectrum has a S/N of 80-100 so it should not introduce additional random noise.

3. A mean cross-dispersion profile was determined from the well exposed portion of the detector and each column was divided by it. This adjusts for different exposure times in overlap regions, and assumes that the spectrum does not change significantly across the filled aperture.

4. Finally, each row was divided by a 512 point smoothed version of itself. This is done to isolate only the high frequency noise, i.e., the P-flat structure.

The end products of the process described above are shown in Figures 4 – 7 for the FUVA and Figures 8 – 11 for the FUVB. Only G130M data were used to construct the FUVA images and only G160M data were used for the FUVB images.

3.2 Producing a gain map

A gain map is simply an image of the median pulse height amplitude (PHA) produced by a single photon at each detector pixel. As a pixel is exposed to more and more light, charge is extracted from the detector cathode, causing the pulse height produced by a single photon to decrease. This decrease is called gain sag. The effect can be alleviated somewhat by increasing the high voltage (HV).

The deuterium data were particularly useful for producing gain maps because the entire detector was illuminated at the same time, providing a snap shot of the gain over the detector at that time. To produce the gain maps, the data were first binned by two in both X and Y to increase the signal, and then all events in each binned pixel were used to construct pulse height distributions (PHDs). The PHDs were then fit by Gaussians to determine their peaks (the modal gain). For pixels with too few events to obtain a good fit, the gain was interpolated from adjacent pixels.

The upper stripe in Figure 12 shows a part of a gain map derived from the deuterium data for the FUVB. We concentrate on the FUVB, since it was exposed to the intense Lyα air glow, which created far more localized gain sag than did the exposure to the SEDs of most targets. The portion of the FUVB shown contains the air glow of the most used G130M CENWAVE settings. The extreme low gain regions near X = 5000, 6000, 7000, 8000 and 9000 are due to the default FPPOS = 3 settings of CENWAVE = 1327, 1318, 1309, 1300 and 1291, respectively. The other low gain regions, spaced roughly 250 pixels apart, are due to Lyα from the other, lesser used, FPPOS settings.
**Figure 4.** Normalized FUVA detector images.
Figure 5. FUVA detector images (continued).
Figure 6. FUVA detector images (continued).
Figure 7. *FUVA detector images (continued).*
Figure 8. Normalized FUVB detector images.
Figure 9. FUVB detector images (continued).
Figure 10. FUVB detector images (continued).
Figure 11. FUVB detector images (continued).
In the next section, we will need an estimate of how the gain maps change with time (usage). To accomplish this, we simply interpolated the observed gain maps in $Y$ across the portion of the detector which has been affected by gain sag. This provides an estimate of the detector gain at launch. The result is shown as the middle stripe in Figure 12, where it has been displaced in $Y$ by $-200$ pixels for display purposes. Next, the gain sagged map was subtracted from the interpolated map and divided by the number of years between launch and the deuterium observations (2.16 years). The result is a map of the rate of gain sag (PHA decrease) per year over the detector – assuming the future exposure to light will be similar. The lower stripe in the figure is the negative of this quantity displaced by $-400$ pixels in $Y$ for display.

Finally, we note that similar maps were produced for the G130M FUVB data obtained at the higher HV setting. These are useful for estimating how changing the HV affects gain sag.

4. Analysis

In this section, we discuss applications of the data sets described in the previous section. Specifically, how they are used to determine the bad pixel table, construct a model of the expected lifetime at different detector locations and estimate the effect of misregistration in $Y$ on 1-D P-flats.
4.1 Determining the bad pixel table

The 2-D images were used to determine detector locations that are relatively free of bad pixels and, subsequently, to update the Bad Pixel Reference Table (BPIXTAB), which identifies regions on the detector that should be excluded from the final calibrated products due to data quality issues. The broad coverage of the data in the \( Y \) direction permitted a large number of new features to be identified in regions of the detector not previously illuminated.

In particular, new dead spots and questionable spots were identified and assigned data quality flags (DQ) of 16 and 1024, respectively. Questionable spots were determined by marking any region where the response falls below 50% in the normalized 2-D images shown in Figures 4 – 11. Similarly, bad spots were identified as regions where the response was below 20%. Consequently, all dead spots are questionable, but all questionable spots are not bad. The differentiation of these two levels of poor response is important because they require different correction strategies. Dead spots will simply be excluded from processing since they typically contain many pixels with zero response, which cannot be corrected with any sort of flat field. However, questionable spots typically have low, but non-zero, response and could be corrected with an appropriate flat field.

The large \( Y \) coverage also allowed an extended view of the grid-wire shadows that span the detector. This made it clear that five regions previously marked and corrected as grid-wire shadows on the FUVB are not consistent with grid-wire behavior over the whole range of \( Y \). While it was previously known that these regions were not caused by grid-wires, their corrections had been implemented with the grid-wires since they did not change with \( Y \) over the \( Y \) range of the original lifetime position. However, this is not the case over the entire detector, so the corrections must now be separated. As a result, these five regions will no longer be flagged as grid-wires nor corrected within the grid-wire flat field. Instead, they will be flagged and corrected as questionable spots (1024). The five regions in question appear near \( X = 1480, 1568, 1647, \) and 1733 (see Figure 8), and 14739 (see Figure 11).

4.2 Modeling expected lifetimes

The gain maps discussed in section 3.2 were used to construct a model of how continued usage affects the COS FUV detectors, and to examine different strategies concerning where to place the spectrum for subsequent lifetime positions. The starting point of all these investigations was to first estimate the gain at the time we expected to make the first lifetime position move, July, 2012. To accomplish this, we used the gain sag/year image presented in Figure 12 to extrapolate the effect of usage at the initial location until the time of the move. Then, beginning with this image, the gain sag/year map was shifted in \( X \) and \( Y \) and scaled by time to determine the best position for the new lifetime location. When assessing potential new locations, additional factors had to be considered, such as how accepting some damaged regions at the new location would
potentially increase the number of future lifetime positions available and how the focus changed with X and Y position. A full discussion of these and other issues which influenced our final selection of lifetime positions is contained in Oliveira et al. (2013).

The gain sag measured from the deuterium observations obtained at the lower voltage settings was used to create a map of the amount of gain lost at the time of the deuterium observations. This was done by taking the difference of the observed gain sag and the interpolated gain sag. The result is a map of mostly negative numbers, representing the amount of gain lost since launch. This was then divided by the number of years since launch to give a map of the gain sag per year at the original operation position, $\Delta g$.

Once $\Delta g$ was in hand, the impact of continued use for another $\Delta T$ years was estimated at the initial location by simply multiplying $\Delta g$ by $\Delta T$ and adding it to the observed gain map.

The effect on gain sag of using the detector for $\Delta T$ years at a location positioned $\Delta X$ and $\Delta Y$ from the current position was estimated as follows:

1. The initial map was “aged” at the current location, as described above.
2. The $\Delta g$ map was shifted by $\Delta X$ and $\Delta Y$ to center it at the desired location.
3. The $\Delta g$ map was multiplied by the time it would operate that that location.
4. The $\Delta g$ map was added to the gain sag map at the time of the move.

Figures 13 – 16 show examples of the results. From a strictly gain sag perspective, it was determined that the position which would result in the least detector damage and allow the closest packing of lifetime positions, was a move in the minus $Y$ direction together with an offset in $X$, so that the dead spots caused by Ly $\alpha$ would not overlap. However, the additional lifetime this move allowed compared to other locations is small.

Figure 17 summarizes how moving to different locations affects the performance of the FUVB at the location of the G160M after 2 years of use. We show this case since the FUVB is affected by the Ly $\alpha$ holes and the G160M is narrow in $Y$, so it is strongly affected by dead pixels. The figure shows that for $\Delta X = 0$, just about any move with $|\Delta Y| \geq 20$ is equivalent to within a few percent, since most of the previously damaged pixels are avoided. In addition, the gains in lifetime achieved by movements in $X$ are quite small.

The preceding results had to be considered together with accompanying differences in spectral resolution, which also changes with location. When taken together, it was decided that a move in the positive $Y$ direction with $\Delta X = 0$ would preserve the current spectral resolution and only degrade the expected lifetime by a very small amount compared to other possible moves. Oliveira et al. (2013) describe the entire decision process in more detail.
Figure 13. Images of the pulse heights expected for the FUVB 1.5 years after moving. Top: $\Delta X = 0$, $\Delta Y = +30$. Bottom: $\Delta X = 0$, $\Delta Y = -30$. The horizontal black lines indicate the assumed centroids of the potential new positions. Most of the active area is shown, and “Ly α holes” are clearly evident.
Figure 14. Same as Figure 13 showing details in the regions of the Ly $\alpha$ holes.
Figure 15. Same as Figure 13 for $\Delta X = -125$, $\Delta Y = +30$ (top), and $\Delta X = -125$, $\Delta Y = -30$ (bottom).
Figure 16. Close up of the Ly $\alpha$ holes seen in Figure 15.
**Figure 17.** Summary of FUVB gain sag degradation after 2 years at a new G160M location. Top: For different $\Delta Y$ moves (with $\Delta X = 0$) the figure gives: the fraction of pixels considered dead, with PHA $\leq 3$, (black); the fraction of 21 $Y$ pixel tall columns (the approximate width of G160M spectra on the detector) containing bad pixels (blue), and; the fraction columns with half or more of the pixels with PHA $\leq 3$ (red). Bottom: similar to the top except for moves in $\Delta X$ with $\Delta Y = 35$. 
5. Summary

We have used the observations from the calibration program 12676 to produce an image of the detectors over the region accessible for science and an on orbit gain sag map of the detectors before most of their surfaces are affected by gain sag. These data were used to create a new bad pixel table, and a quantitative model of how gain sag will affect subsequent lifetime positions.

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References

Oliveira, C. et al., 2013, COS Instrument Science Report 2013-12