

# FUV Focus Sweep Exploratory Program for COS at LP4

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Paule Sonnentrucker<sup>1,2</sup>, Andrew Fox<sup>1</sup>, Steve Penton<sup>1</sup>, Cristina Oliveira<sup>1</sup>, Julia Roman-Duval<sup>1</sup>, David Sahnou<sup>1</sup>

<sup>1</sup>Space Telescope Science Institute, Baltimore, MD

<sup>2</sup>European Space Agency

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## ABSTRACT

*As part of the exploratory phase of the move of COS/FUV operations to Lifetime Position 4 (LP4), we designed program 14527 to measure changes in the focus offsets required to optimize spectral resolution at the prospective LP4 position (-5.02" from LP1 in cross-dispersion direction). Following the successful strategy established in program LENA2 (P13635, LP3 move), we executed one focus sweep using the G130M/1222 configuration (FUVB only) and two sweeps using the G130M/1309 configuration (FUVA and FUVB treated separately). The target Feige 48 was observed in this program for a total of 4 external orbits. As previously, we used an auto-correlation method to derive the focus offsets relative to LP3 that maximize spectral resolution at LP4 for the G130M/1309 and G130M/1222 settings. We find that a focus offset value of +40 steps relative to LP3 maximizes spectral resolution at LP4 for the G130M/1309 configuration (FUVA and FUVB combined). For G130M/1222 (FUVB only), the adopted focus offset value that maximizes spectral resolution at LP4 is of +142 steps from the relative to LP3. These values were patched into a FSW update to LV0058 on December 17, 2016 (2016.354) and were permanently installed as part of LV0059 on May 8, 2017 (2017.128).*

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## 1. Introduction

Since the beginning of its on-orbit operations the COS FUV detector has experienced sustained gain sag at the location used for science operations. Starting in Cycle 18, HST users were required to use multiple FP-POS positions when observing with the COS FUV detector in order to minimize the effects of localized gain sag on the science data quality at the original lifetime position (aka “lifetime position 1” or LP1). Owing to the accelerated rate at which gain sag affected the FUV data on local scales and to maintain optimum science data quality, a series of exploratory and enabling programs were executed during Cycle 18 (see Osten et al. 2013; Oliveira et al. 2013; Proffitt et al. 2013) in order to determine the number of additional lifetime positions available for FUV science operations and to select the next best lifetime position at which to continue science operations. The move to LP2 took place on July 23, 2012 and the move to LP3 took place on February 9, 2015.

Each of these lifetime position (LP) moves comprises three major phases: an exploratory phase, an enabling phase and, once the move to a new LP is performed, a calibration phase that verifies smooth operations and data quality. The COS Team is currently preparing the move of FUV operations to lifetime position 4 (LP4) which is slated for Fall 2017. Program 14527 (P14527) is part of the exploratory phase of the COS/FUV move of operations to LP4. It is designed to measure the focus offset values relative to LP3 for the G130M/1309 and G130M/1222 settings at the prospective position of LP4 on the FUV detectors (-5.02" from LP1 in the cross-dispersion direction). Prior knowledge of these focus values is required for the successful execution of two additional optimization programs designed to 1) finalize the LP4 location on the FUV detectors (P14841) and 2) to spot-check the spectral resolution and extend the geometric distortion corrections (P14842) to the entire detectors. In this ISR, we summarize the results of the analysis of the focus sweeps performed in P14527.

## 2. Observations

Similarly to the focus sweeps for LP2 (P12796; PI Oliveira) and LP3 (P13635; PI Fox), this LP4 exploratory focus sweep program consisted in observing the bright

external target Feige 48 (V-KL-UMA) with the G130M/1309 and G130M/1222 (FUVB only) configurations for a total 4 orbits. Feige 48 proved to be an ideal target to perform the COS/FUV focus sweeps with the G130M grating due to its low projected rotational velocity and its profusion of UV photospheric lines, a prerequisite for our data analysis which relies on line-width measurements.

A focus sweep optimization analysis was performed during the LP3 enabling phase (P13635) and indicated that the most efficient and most accurate sweep structure for the G130M grating consisted in performing a 10-point sweep with focus offset values ranging from -800 to +1000 in 200-step increments. The zero point of the sweep corresponded to the focus value of 1309 at LP2. We adopted this same strategy in P14527 when performing the G130M/1309 sweeps. The zero point of the current sweep corresponds to the focus value of 1309 at LP3. As in previous programs, sweeps for segments A (FUVA) and B (FUVB) were taken separately but consecutively to alleviate potential global count rate violations when using both segments together. Note that for this program the G130M/1222 sweep consisted of a 9-point structure only; the last positive point in the sweep was omitted to allow the G130M/1222 observations to fit within 1 orbit. The G130M/1222 sweep was performed with FUVB only (FUVA off) to optimize the focus at the shorter wavelengths accessible with FUVB alone.

At the time this program executed, the parameters defining LP4 were not uploaded in the flight software yet. As a result, each sweep started with a 0.1s science initialization exposure which allowed us to manually perform the following LP4 parameter adjustments:

1. placement of the aperture at LP4 cross-dispersion position on the COS/FUV detector ( $y = -5.02''$  from LP1 or XAPER= +53 steps relative to LP3),
2. placement of the external target within the aperture once positioned at LP4 (POS TARG Y =  $-2.52''$  defined from nominal LP3 position);
3. setting FUVA to HV=167 during the G130M/1309 FUVA sweep,
4. setting FUVB to HV=163 during the G130M/1309 FUVB sweep,
5. setting FUVB to HV=167 during the G130M/1222 FUVB; and
6. setting the absolute FOCUS position for the relative FOCUS special commanding offsets during each focus sweep.

Note that WAVECAL=NO was set during the initialization exposure to override the default lamp exposure length of 12s for these settings.

The data were successfully obtained on July 12-13, 2016 with the G130M/1309 FUVA taken first, followed by the G130M/1309 FUVB and finally the G130M/1222 FUVB. Table 1 summarizes the exposure IDs associated to the G130M/1309 and G130M/1222 observations, the time of observations, the commanded focus offsets with respect to LP3, and the breathing-corrected focus offsets used in the analysis and discussed in the next section.

**Table 1:** Log of exposures and focus offsets in LP4 optimization program P14527

Exposure ID	Segment/Cenwave	Start Time (UT)	Commanded Focus Offset* Relative to LP3	Breathing-Corrected Focus Offset*
ld4j01kpq	FUVA/1309	07/12/16 23:10	-800	-830
ld4j01krq	FUVA/1309	07/12/16 23:16	-600	-617
ld4j01ktq	FUVA/1309	07/12/16 23:23	-400	-405
ld4j01kvq	FUVA/1309	07/12/16 23:29	-200	-197
ld4j01kxq	FUVA/1309	07/12/16 23:36	0	8
ld4j01kzq	FUVA/1309	07/12/16 23:42	200	215
ld4j01lfq	FUVA/1309	07/13/16 00:36	400	348
ld4j01lkq	FUVA/1309	07/13/16 00:43	600	554
ld4j01lnq	FUVA/1309	07/13/16 00:49	800	770
ld4j01lpq	FUVA/1309	07/13/16 00:56	1000	981
ld4j01lsq	FUVB/1309	07/13/16 01:07	1000	1004
ld4j01lvq	FUVB/1309	07/13/16 01:15	800	808
ld4j01mlq	FUVB/1309	07/13/16 02:11	600	549
ld4j01mnq	FUVB/1309	07/13/16 02:16	400	352
ld4j01mpq	FUVB/1309	07/13/16 02:22	200	161
ld4j01mrq	FUVB/1309	07/13/16 02:27	0	-28
ld4j01mtq	FUVB/1309	07/13/16 02:32	-200	-221
ld4j01mvq	FUVB/1309	07/13/16 02:37	-400	-409
ld4j01mxq	FUVB/1309	07/13/16 02:42	-600	-598
ld4j01mzq	FUVB/1309	07/13/16 02:47	-800	-798
ld4j02n9q	FUVB/1222	07/13/16 03:57	-1000	-1053
ld4j02nbq	FUVB/1222	07/13/16 04:01	-800	-844
ld4j02ndq	FUVB/1222	07/13/16 04:06	-600	-635
ld4j02nfq	FUVB/1222	07/13/16 04:10	-400	-412
ld4j02nhq	FUVB/1222	07/13/16 04:15	-200	-209
ld4j02njq	FUVB/1222	07/13/16 04:19	0	-5
ld4j02nlq	FUVB/1222	07/13/16 04:24	200	197
ld4j02nnq	FUVB/1222	07/13/16 04:28	400	398
ld4j02n9q	FUVB/1222	07/13/16 04:33	600	603

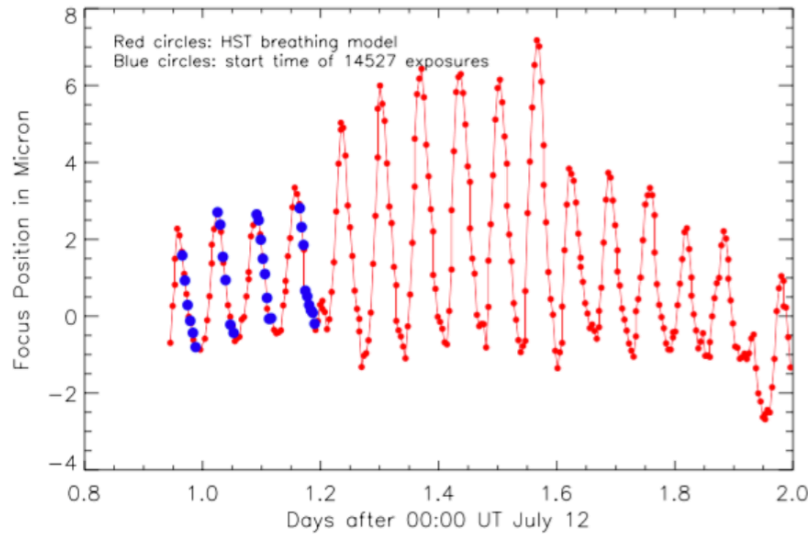
\* The actual value of the focus offsets as reported by the telemetry item LOFMSTP, could vary by up to 13 steps due to mechanism positioning uncertainty.

### 3. Data Analysis

The HST Optical Telescope Assembly (OTA) while remarkably stable, does experience noticeable changes in focal length due to variations of the separation between the two HST mirrors due to temperature fluctuations on timescales that can be shorter than an orbit. As a result, the focus at which HST observations are taken at any given time is different from the focus value commanded by the flight software. These focus variations, also called breathing, are routinely monitored (e.g., Lallo et al. 2010) and a model of the breathing correction as a function of time has been

incorporated into an online tool available at: <http://focustool.stsci.edu/cgi-bin/control.py>. As in previous analyses (e.g., Fox et al. 2015), we used this tool to calculate the breathing-corrected focus at the start of each exposure comprising our focus sweeps (see Table 1). Figure 2 displays the HST focus offsets (in microns) with respect to the nominal model (red line) for the time period in which P14527 was executed. The blue points represent the starting time for each of the 29 exposures taken in this program. The focus offsets returned by the model are multiplied by a factor 19.2 (see Oliveira et al. 2014) to convert the breathing corrections into units of COS/OSM1 focus steps and the sense of the correction has the form:

$$\text{breathing-corrected focus offset} = \text{commanded focus offset} - \text{breathing correction}$$



**Figure 1:** Evolution of the HST offset focus position (in microns) as a function of time during execution of P14527. The red curve displays the HST breathing model derived for WFC3/UVIS1 and applicable to COS. The blue points indicate the start time of each exposure comprising the G130M/1309 and G130M/1222 focus sweeps.

Additionally, the COS focus mechanism does not always travel to the exact commanded position. The telemetry keyword LOMFSTP returns the actual focus position of the mechanism as measured on-board instruments. This additional offset can be as large as  $\pm 20$  focus steps. For the observations of P14527, this additional offset was determined to be no more than  $\pm 13$  steps.

The best focus offset values (relative to LP3) were derived using the auto-correlation function (ACF) method following Lennon et al. (2010) and Oliveira et al. (2013). In brief, this method relies on selecting specific spectral regions containing narrow isolated absorption lines that are cross-correlated against themselves. The width of the ACF represents a measure of the width of spectral lines in each region and thus the spectral resolution. The best focus offset value is subsequently found for the exposure within the sweep that returns the narrowest ACF width, which in turn corresponds to the sharpest spectral lines and the best focus offset for that particular wavelength range.

For the G130M/1309 and G130M/1222 sweeps, the ACF widths were determined by

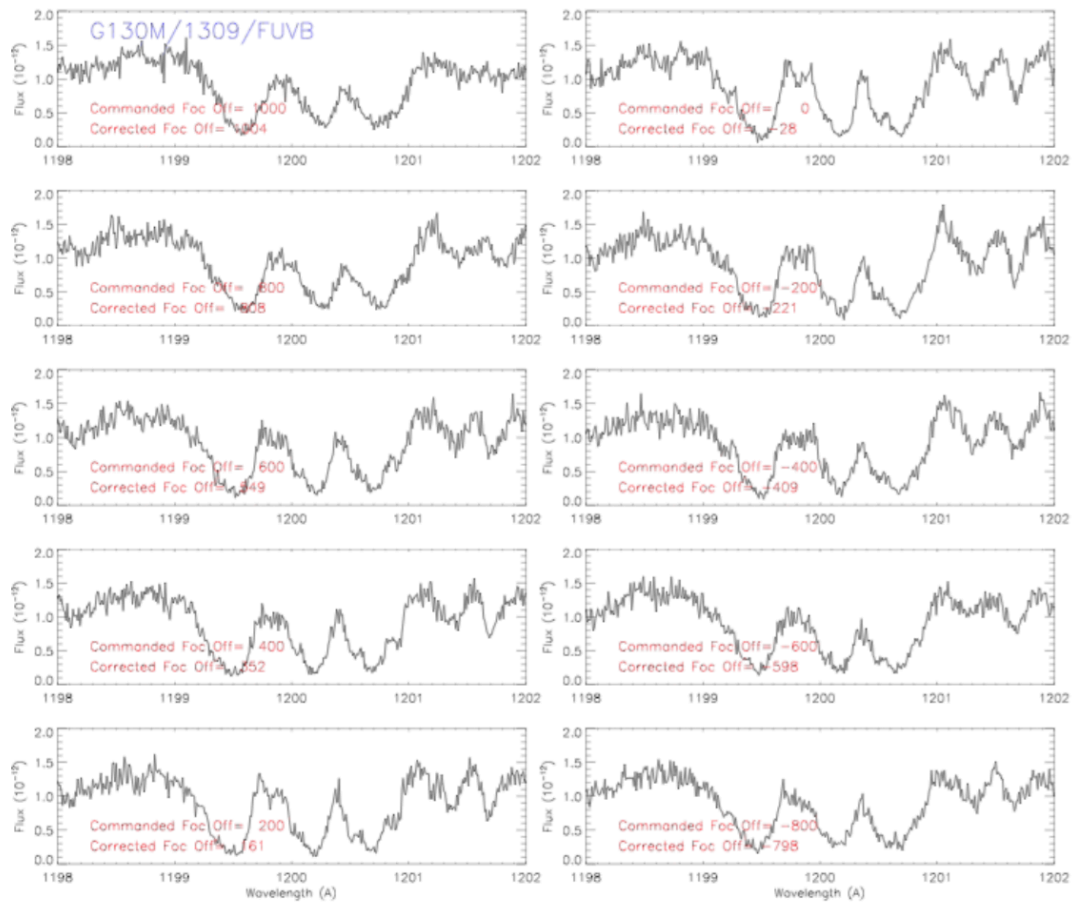
fitting a Gaussian function to the peak of the ACF for each exposure in a given sweep as described in Fox et al. (2015). The spectral windows used in this ISR are listed in Table 2 and are very similar to the windows adopted by Fox et al. (2015) as well. Since the ACF technique samples the focus curve over a range in wavelength, we are effectively optimizing resolution for the *average* wavelength within the chosen spectral windows.

The analysis generated 5 ACF curves for the G130M/1309 setting (2 for FUVB and 3 for FUVB) and 2 ACF curves for the G130M/1222 setting (FUVB only). For each spectral window we derived the minimum of the ACF curve using a cubic fitting function. The focus offsets corresponding to these minima are reported in the last column of Table 2. Note that since the focus is wavelength dependent, each spectral window returns a slightly different and averaged value of the best focus offset.

**Table 2:** Wavelength ranges used for the auto-correlation analysis and associated best focus offsets (in steps) relative to LP3 derived from cubic fits to the ACF curves.

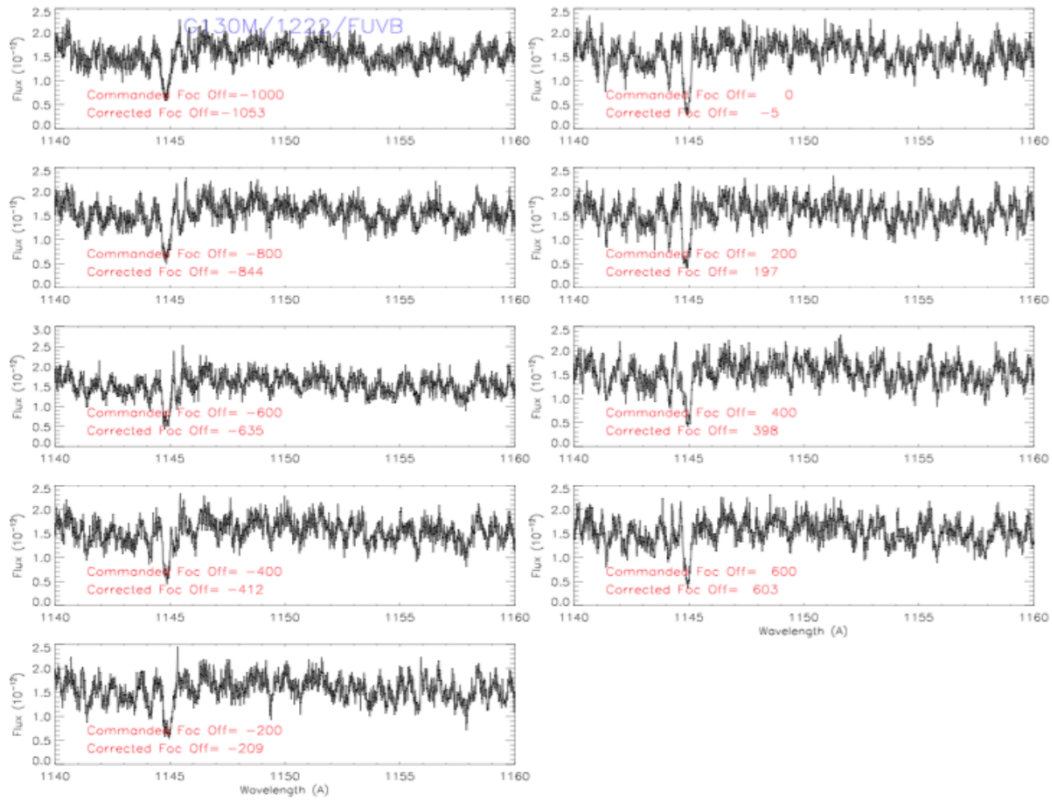
G130M/1309	$\lambda$ Range (Å)	Focus Offset (from LP3)
FUVB	1160-1173	-24
FUVB	1226-1243	+104
FUVB	1262-1286	-61
FUVA	1344-1391	+116
FUVA	1404-1437	+112
FUVB + FUVA	---	+35
<b>Adopted</b>		<b>+40</b>
G130M/1222	$\lambda$ Range (Å)	Focus Offset (from LP3)
FUVB	1146-1162	+141
FUVB	1185-1205	+71
<b>Adopted</b>		<b>+142</b>

Figures 2 & 3 display a sub-sample of the Feige 48 spectra obtained at each point in the focus sweep for G130M/1309 (FUVA) and G130M/1222 (FUVB) for 2 of the spectral regions chosen for this analysis (see also Appendix A).



**Figure 2:** Interstellar absorption lines in the region of the N I triplet observed in COS FUV spectra of the star Feige 48 in the G130M/1309/FUVB setting. Each of the ten panels show the spectrum obtained at a given position in the focus sweep with commanded and breathing-corrected focus offsets annotated in red. The fluxes are in units of  $\text{erg s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}$ . The best-fit focus for this setting determined from our auto-correlation analysis is measured at +40 steps relative to the LP3 focus value.



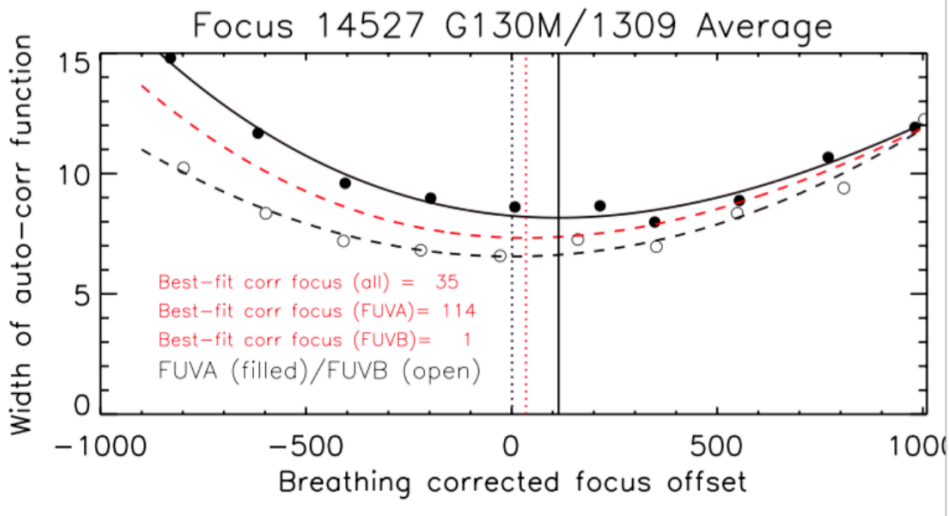


**Figure 3:** One of the two spectral regions used to perform the ACF analysis for the G130M/1222, FUVB setting. Each panel shows the Feige 48 spectrum obtained at a given focus offset within the focus sweep range. The values of the commanded focus and the breathing-corrected focus are reported in each panel for reference. The best-fit focus for this setting determined from our auto-correlation analysis is measured at +142 steps relative to the LP3 focus value.

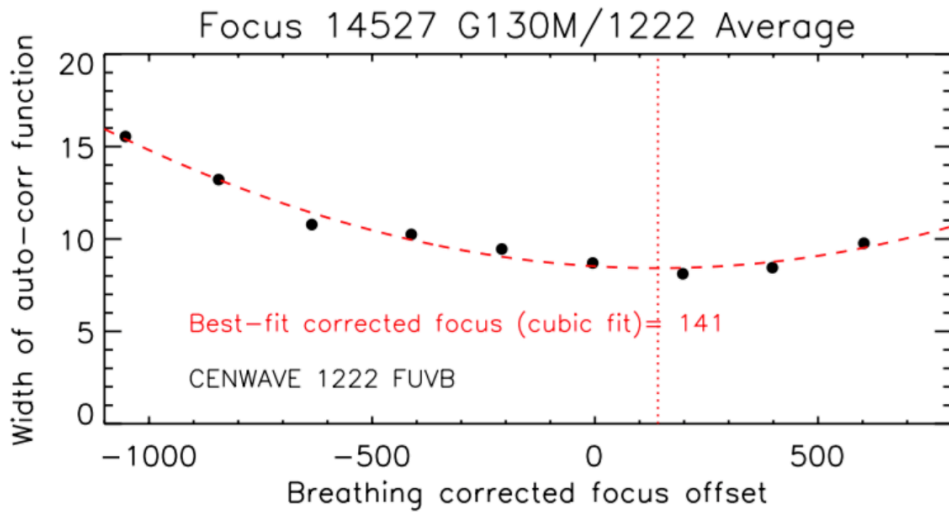
## 4. Results

Figure 4 displays the average ACF width curves derived from the analysis of the G130M/1309 FUVB (open symbols) and FUVB (filled symbols) data as a function of breathing-corrected focus. The minimum width of each average curve was derived by fitting a cubic relation to the FUVB distribution (dashed black line) alone, to the FUVB distribution (solid black line) alone and then to the combined FUVB + FUVB distributions (all, dashed red line). The result for each curve is indicated by a vertical line and the focus offset relative to LP3 corresponding to each minimum is reported at the bottom left.





**Figure 4:** Width of auto-correlation function (ACF) as a function of breathing corrected focus for the G130M/1309 FUVB (filled circles) and FUVB (open circles). The black lines represent the best cubic fit to the data for each segment separately. The red dashed line represents the best cubic fit to the data when both segments are combined. The vertical black lines indicate the minimum in each distribution which corresponds to the best focus offset for each segment. The best focus offset (relative to LP3) for the G130M/1309 setting is derived by fitting all data points.

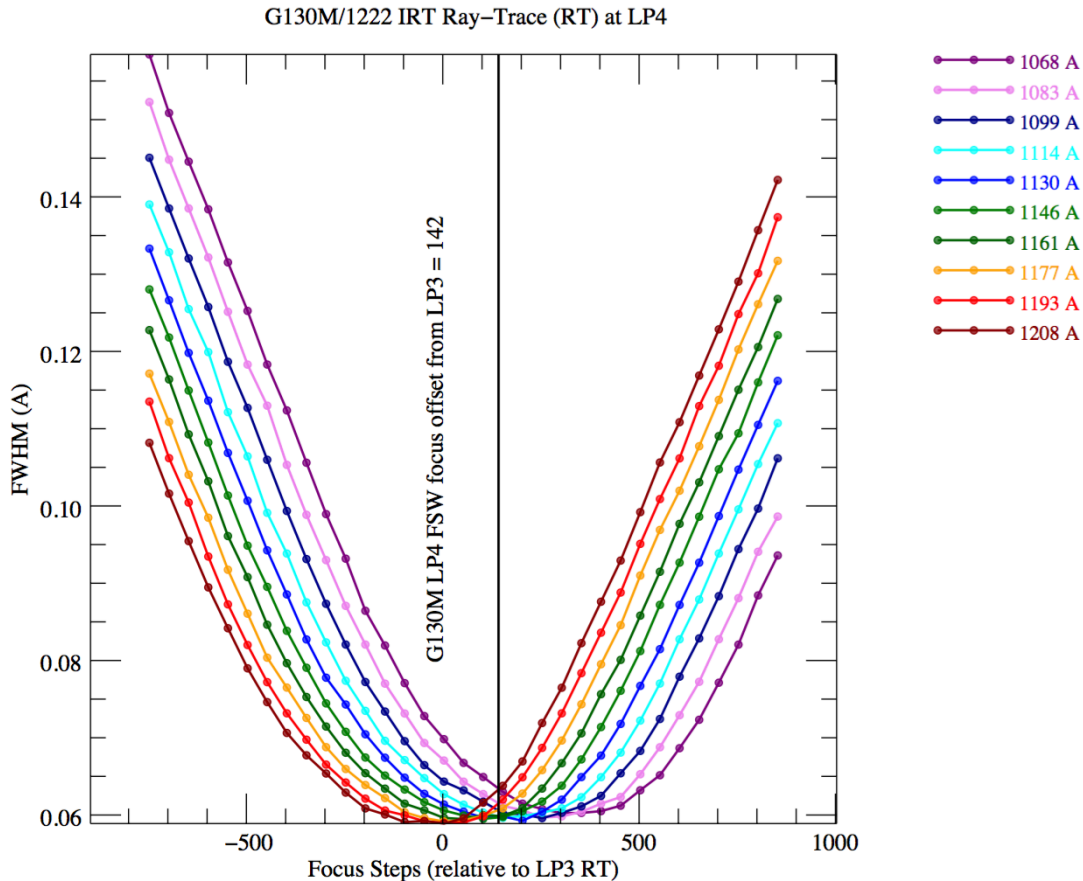


**Figure 5:** Width of auto-correlation function (ACF) as a function of breathing corrected focus for the G130M/1222 FUVB (filled circles). The dashed line represents the best cubic fit to the data. The vertical dotted line indicates the minimum of the cubic fit and corresponds to the best focus offset value (relative to LP3) for the G130M/1222 FUVB setting.

For the G130M/1309 configuration, the best focus offset was derived by combining all 20 points (red dashed curve) and was estimated to be at +35 focus steps from LP3 (Table 2, Figure 4). For the G130M/1222 setting, Figure 5 shows the average ACF width curve derived for FUVB (filled symbols) as a function of breathing-corrected focus along with the best cubic fit to the average curve (red dashed line). The best

focus offset is derived to be at +141 steps from LP3.

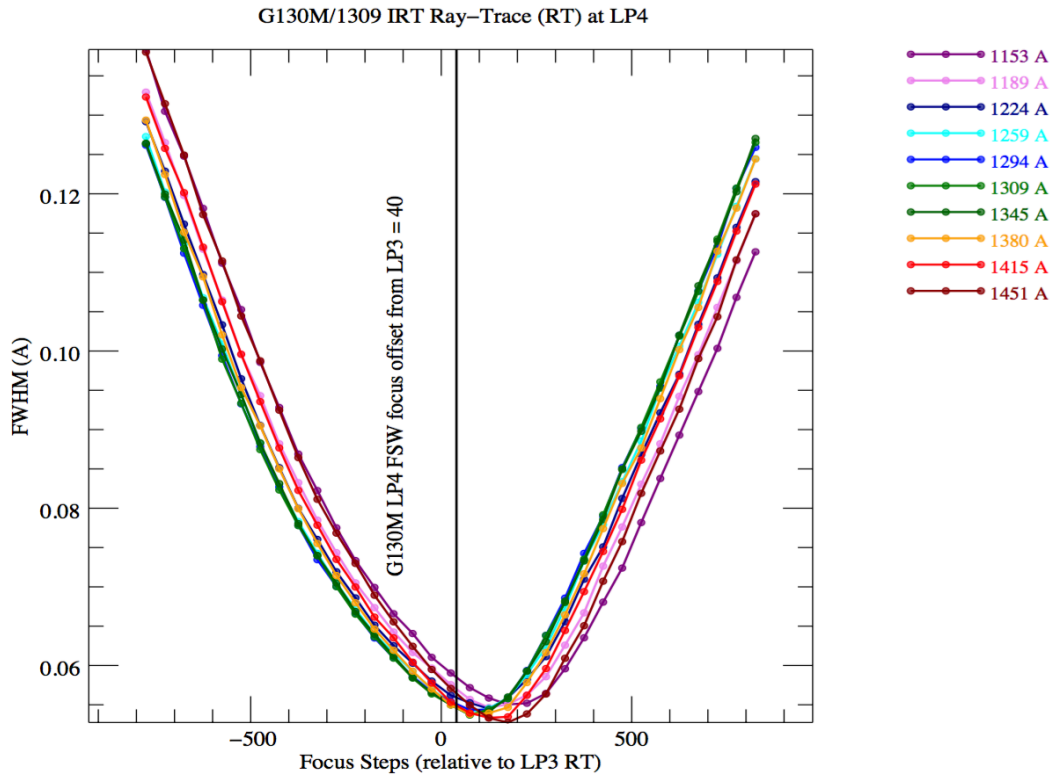
The results of the measurements were then compared with the focus offset predictions from Ray-Trace (RT) models (Interactive Ray-Trace; Cash 1989) generated assuming that LP4 operations would take place at a cross-dispersion position of -5.02" relative to LP1 on the COS/FUV detector. Figure 6 displays the ray-trace model predictions for the G130M/1222 setting relative to LP3. The figure shows the amplitude and direction of the predicted changes of focus value with wavelength, when adopting a focus sweep structure similar to those performed in P14527. For this setting, the model predicts that the focus value increases with decreasing wavelength, a behavior consistent with our measurements (see Table 2). Since for this setting the spectral resolution was optimized around 1160 Å (see Fig. 5.5 of COS Instrument Handbook), we compared the focus offset value we measured around 1160 Å (+141 steps, see Table 2) with the value predicted by the RT at that wavelength (+142 steps, black line in Fig. 6) and found that they were fully consistent. For the G130M/1222 setting, we therefore adopted a focus offset value of +142 steps relative to LP3, as returned by the RT.



**Figure 6:** Ray trace model predictions for the best focus value relative to wavelengths for the G130M/1222 configuration. The focus values are given relative to LP3. The line indicates the adopted offset value for LP4.

Figure 7 displays the ray-trace model predictions for the G130M/1309 setting. In this

case, the RT predicts a much smaller variation of the focus value with wavelength (within 200 steps), a slight decrease of the focus values with decreasing wavelength and a best focus value of +40 steps at 1309 Å, the middle of the observed wavelength range when FUVB and FUVB are combined, as we did on our analysis. This predicted trend is also observed in our measurements. When combining measurements from both segments, we obtained a focus value of +35 steps, again fully consistent with the RT predictions (+40 steps) for that particular wavelength range. For the G130M/1309 setting, we therefore adopted the focus value of +40 steps relative to LP3, as returned by the RT model predictions. This +40 step offset applies to all five of the original COS G130M central wavelength settings (1291, 1300, 1309, 1318, and 1327) at LP4.



**Figure 7:** Ray trace model predictions for the best focus value relative to wavelengths for the G130M/1309 configuration. The focus values are given relative to LP3. The line indicates the adopted offset value for LP4.

## 5. Conclusions

In preparation for the move of COS/FUV operations to lifetime position 4 (LP4), focus sweeps were performed to derive the best focus offset values relative to LP3 for the G130M/1309 and G130M/1222 settings. An auto-correlation analysis was performed following the methodology applied successfully to previous focus sweeps. For the G130M/1309 setting, we adopted the focus offset value of +40 steps relative to LP3. This offset also applies to the 1291, 1300, 1318 and 1327 cenwaves. For the G130M/1222 FUVB setting, we adopted the focus offset value of +142 steps relative to LP3. These offset values were entered manually in optimization programs P14841

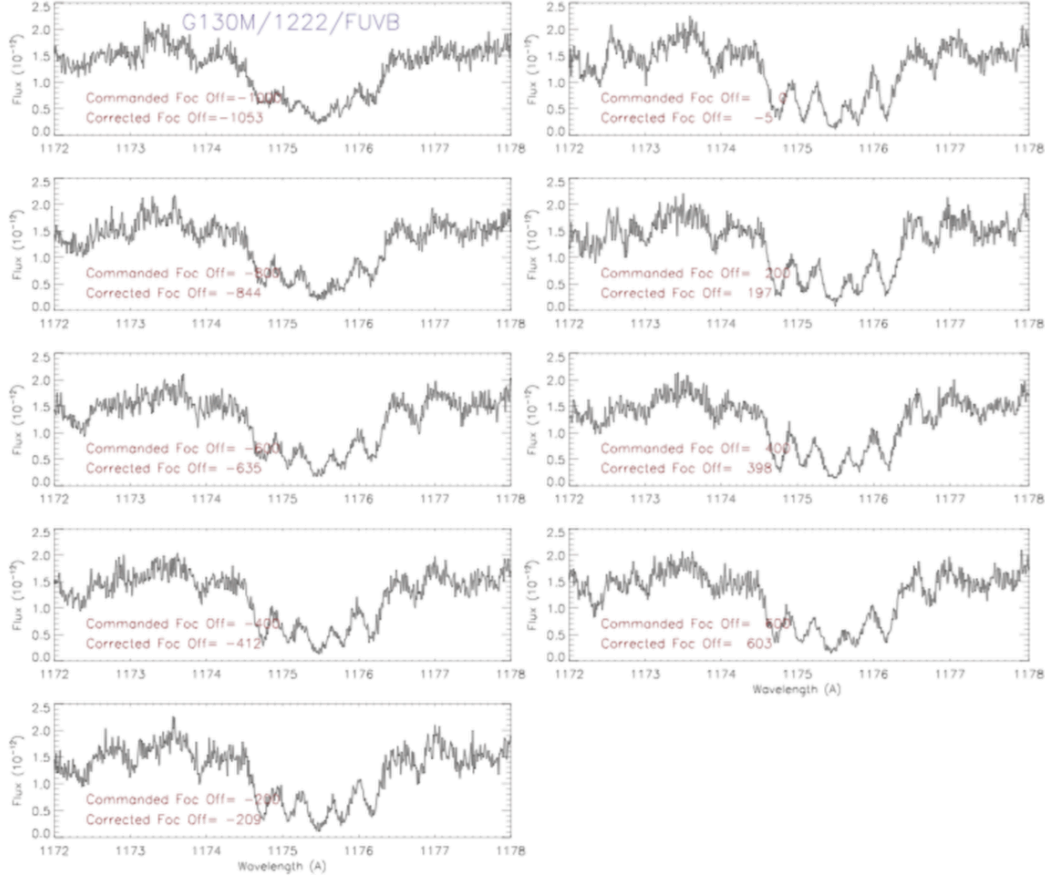
and P14842. They were later patched into a FSW update to LV0058 on December 17, 2016 (2016.354) and were permanently installed as part of LV0059 on May 8, 2017 (2017.128).

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## Appendix A

Figure 8 shows additional examples of wavelength regions exhibiting various ISM and photospheric absorption lines in the Feige 48 spectra for data taken in the sweep using the G130M/1222/FUVB setting. Each panel displays the Feige 48 spectrum at a given focus offset position within the sweep.



**Figure 8:** Absorption lines of the photospheric C III triplet observed in COS FUV spectra of the star Feige 48 using the G130M/1222/FUVB setting. The 9 panels show the spectra obtained at each position in the focus sweep (with commanded and breathing-corrected focus offsets annotated in red). The fluxes are in units of  $\text{erg s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}$ . The best-fit focus for this setting determined from our auto-correlation analysis is measured at +142 steps relative to LP3.