ABSTRACT
We report the results of the COS/FUV calibration program LCAL4 (ID 13933), designed to verify operations and performance of the bright object aperture (BOA) at the third lifetime position (LP3). The bright standard star G191–B2B was observed in February 2015 with the G130M/1291, G160M/1623, and G140L/1280 settings. The spectral resolution and cross-dispersion (XD) profiles were measured with each setting, and compared to those measured at LP2. The LP3 XD profiles are found to be very similar in shape to those at LP2. The BOA spectral resolution at LP3 for the G130M grating is determined by a line-width analysis to be $d\lambda=0.21–0.22 \text{Å} \ (\text{FWHM})$, corresponding to a resolving power $R \approx 5800$, with no difference between the values measured at 1193 and 1260 Å. This compares to $d\lambda=0.14 \text{Å} \ (R=9000)$ measured at LP2 and $d\lambda=0.17 \text{Å} \ (R=7000)$ at LP1. For G160M, we determine $d\lambda=0.10–0.13 \text{Å}$ at 1548 Å, ($R=11900–15000$), and we show this is essentially unchanged from LP2.
1. Introduction
COS is optimized for spectroscopy of faint point sources. However, the bright object aperture (BOA) is available for observations of bright targets that would exceed the allowed UV count rates if observed with the primary science aperture (PSA). The BOA is a 2.5-arcsecond diameter neutral-density filter made from a wedge of Magnesium Fluoride (MgF$_2$) inserted into the optical path after the OSM (optics select mechanism). It has an average transmission of $\sim 0.6\%$ in the UV. In addition to attenuating the UV light from the source, it degrades the spectral resolution relative to observations taken with the PSA, which is located 13″ away in the cross-dispersion direction.

When moves to new COS FUV lifetime positions take place, a series of calibration programs (known as the LCAL programs) is executed to characterize and calibrate spectra taken at the new position. In this ISR, we report on the results of the BOA verification program LCAL4 (Program ID 13933) designed to determine the performance of the BOA at the Third Lifetime Position (LP3), which is located at a position of $-2.5\arcsec$ relative to LP1 in the cross-dispersion direction (LP2 was located at $+3.5\arcsec$). The program’s goals include measuring the cross-dispersion (XD) profile and spectral resolution in different settings. We compare the BOA performance at LP2 and LP3, and also compare the LP3 XD profiles taken with the BOA with those taken with the PSA. This ISR follows previous reports documenting the BOA performance at LP1 (Program 11489; Ghavamian et al. 2010) and LP2 (Program 12807; Debes 2013).

2. Observations
The bright flux-standard star G191–B2B was observed on 15 February 2015 with a one-orbit COS/FUV visit. G191–B2B is a white dwarf (optical magnitude $V=11.69$) that is regularly observed by the COS/NUV channel as part of sensitivity monitoring programs. It is bright enough in the UV ($F_{1300}=1.3 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$) to be observed with the BOA in all three gratings within one orbit.

The observations consisted of a 13s G140L/1280 exposure with FP-POS=3, a 795s G160M/1623 exposure with FP-POS=3, and four 220s G130M/1291 exposures (one per FP-POS position). During the occultation at the end of the orbit, a single wavecal exposure was taken for G130M/1291/FP-POS=4, followed by wavecals in the G160M/1623 and G140L/1280 settings. The purpose of the wavecal exposures was not to calibrate the wavelength of the LCAL4 science exposure (since the OSM was moved between the science and wavecal exposures), but to measure the BOA-WCA offset. The visit design was essentially the same as that used in the BOA verification program at LP2, documented in Debes (2013), with slight updates to the exposure times.
3. Spectral resolution

The spectral resolution of the data can be determined by two methods. First, via direct fits to the line width of unresolved (narrow), unsaturated interstellar absorption lines (the direct-fit method). Second, by convolving a high-resolution reference spectrum of the target with Gaussian line-spread functions (LSFs) of various width and determining the LSF best able to reproduce the observed line width (the convolution method). One advantage of the convolution technique over the direct fit is that it does not assume the lines are intrinsically unresolved. For this method we adopt the STARCAT STIS echelle spectrum of G191–B2B as the reference, described and available at https://archive.stsci.edu/prepds/starcat/.

For G160M and G140L, observations were only taken at one FP-POS position, so the x1d and x1dsurn files are equivalent for our purpose. For G130M, all four FP-POS positions were used. In this case, the resolution can either be determined on the individual x1d files or on the co-added spectrum, which has approximately twice the S/N. In our analysis, we measure the spectral resolution in the co-added G130M file, but we also check the values in each individual FP-POS exposure. We conducted our own manual co-add instead of using the x1dsurn file produced by calcos, since it was necessary to apply wavelength offsets before stacking the spectra to align all the exposures (this was because the auto-wavecal was switched off to maximize on-source exposure time, with the manual wavecal added into the occultation at the end of the orbit).
Figure 1. Measurement of the BOA spectral resolution with the G130M/1291 grating using the profile of interstellar Si II 1260 absorption. The top four panels show the data in the x1d files at each FP-POS position, with Gaussians fits to the absorption plotted as solid red lines. The fifth panel shows a manually-combined spectrum formed by aligning the FP-POS=1, 2, and 3 spectra to the FP-POS=4 spectrum and then co-adding them (shift-and-stack); here the colored lines show the reference STARCAT spectra convolved with Gaussian profiles of three different widths. The spectral resolution as measured by direct fits to the absorption is annotated on each panel as $d\lambda$ (FWHM) and $R=\lambda/d\lambda$. The offset in the central wavelength of the Si II line in the top (FP-POS=4) panel compared to the other panels is a result of the wavecal exposure being taken at FP-POS=4, and does not affect the measurement of the resolution.
The results are presented in Figures 1 and 2 for G130M (using the Si II 1260 and Si II 1193 interstellar lines, respectively) and Figure 3 for G160M (using the C IV 1548, 1550 doublet). These lines were chosen since they are the strongest ISM lines available in the bandpass covered by each grating. The derived values of the spectral resolution are annotated on the panels, both in the form of linewidths $d\lambda$ (FWHM) and resolving power $R \equiv \lambda/d\lambda$ at the wavelength of the lines used. For G130M/1291, using the direct-fit method to the shift-and-stack data, we determine $d\lambda=0.22\,\text{Å}$ ($R=5700$) from Si II 1260 (Figure 1) and $d\lambda=0.21\,\text{Å}$ (also $R=5700$) from Si II 1193 (Figure 2).
Figure 3. Measurement of the BOA spectral resolution with the G160M/1623 grating using the C IV 1548, 1550 doublet. The four colored lines show STIS STARCAT spectra convolved with Gaussian line-spread functions of different line width. This case differ from the determination of the G130M resolution since the C IV lines are resolved (i.e. the observed width is broader than the instrumental line width). The analysis of the C IV 1548 and 1550 profiles gives a resolution $d\lambda=0.13 \, \text{Å}$ and $0.10 \, \text{Å}$, respectively.

Using the convolution method gives a similar value $d\lambda \approx 0.20 \, \text{Å}$, i.e. the STARCAT spectrum convolved with a Gaussian with $d\lambda=0.20 \, \text{Å}$ gives a good representation of the data (purple line in bottom panels of Figures 1 and 2). Using the calcos spectrum instead of the shift-and-stack spectrum makes little difference (0.01 Å) to the derived resolution. The derived values of $d\lambda=0.21$–0.22 Å compare to $d\lambda=0.14 \, \text{Å}$ ($R=9000$) measured at LP2 (Debes 2013) and $d\lambda=0.17 \, \text{Å}$ ($R=7000$) measured in SMOV data at LP1 (Debes 2013). This $\approx 35\%$ decline from LP2 to LP3 can be seen visually in Figure 4 (lower two panels), where we directly compare the co-added spectra in the region around Si II 1260 and Si II 1193 for data taken at the two lifetime positions.

For G160M/1623, we determine a resolution in the LCAL4 (LP3) data of $d\lambda=0.10$–0.13 Å ($R \approx 11900$–15000; Figure 3) from the convolution method to the C IV 1548, 1550 doublet. Thus the G160M grating has a higher spectral resolution with the BOA than the G130M grating. Here the direct-fit method cannot be applied since the high-ion C IV lines are intrinsically broad enough to be resolved, i.e. the observed line width is partly astrophysical, not purely instrumental (direct fits give $d\lambda=0.33 \, \text{Å}$ for C IV 1548 and 0.29 Å for C IV 1550). There are no measurements of the G160M resolution in earlier ISRs to compare with, but in Figure 4 (upper panel) we directly compare the x1dsum data taken at LP2 and LP3 in the region around C IV 1548, 1550 and find no substantial change in the resolution. This indicates that the G160M resolution is 0.10–0.13Å (at 1548 Å) at both lifetime positions.
Figure 4. Direct comparison of BOA data at LP3 (LCAL4 program, black) and at LP2 (FCAL4 program, red) for G160M/1623 (top panel) and G130M/1291 (middle and bottom panels). The degradation in spectral resolution for the G130M grating is visible in the width of the interstellar Si II 1260 and Si II 1193 line profiles, and is quantified via the Gaussian fits shown. However, for G160M, there is no noticeable difference in resolution.

4. Flux calibration

To assess the quality of the flux calibration with the BOA at LP3, we compare in Figure 5 COS/G130M/1291 data taken with the BOA at LP3 (LCAL4) with identical data taken at LP2 (FCAL4). The spectra contained in the standard x1dsum files produced by calcos are plotted. We also compare with the CALSPEC reference spectrum (CALSPEC stars are the HST spectrophotometric standards). Each spectrum is binned by 40 pixels for display purposes. The flux calibration agrees closely between all three spectra in the FUV A range 1300–1430 Å. The LP2 and LP3 flux calibrations are both slightly high in the FUVB range 1230–1270 Å compared to the CALSPEC spectrum. The largest departures from the CALSPEC spectrum occur at the bluest wavelengths (<1200 Å), where the LP2 and LP3 flux calibrations both underestimate the true flux by up to ≈20%. Note that currently, the PSA L-flats and flux calibration are applied to BOA observations.
5. Cross-Dispersion Profiles

The cross-dispersion (XD) profiles quantify the distribution of light falling on the detector perpendicular to the dispersion direction. To produce the BOA XD profiles for each LP3 setting, we took each corrtag file from calcos (containing the event list in binary-table format), and converted it into a two-dimensional flat-fielded and dead-time-corrected image in XFULL/YCORR coordinates. Events with pulse-height amplitudes lower than 2 or greater than 23 were filtered out (as in the flt images produced by calcos). The image was then collapsed in the dispersion direction and summed over all x-pixels. Before summing we excluded the regions between 1210 and 1222 Å and between 1297 and 1307 Å to eliminate contamination by geocoronal emission from Lyman-α and OI 1302 (airglow). Such emission fills the aperture and is much more extended in the XD direction than spectra of point sources. We then normalized the XD profiles to their summed values. The choice to conduct this analysis on the corrtag files and not the flt files was made to ensure a like-to-like comparison between the LP2 and LP3 profiles. For the new twozone extraction algorithm in use at LP3, the flt files are trace-corrected, whereas the flt files taken at LP2 with the boxcar extraction algorithm are not trace-corrected (see Proffitt et al. 2015).

We plot the BOA profiles for six settings observed in the LCAL4 program in Figure 6, where a setting is a grating/cenwave/FP-POS/segment combination. We perform single-component Gaussian fits to determine the centroid and width of the profiles for each setting, although the profiles show extended non-Gaussian wings, so these fits are not intended to represent reliable representations of the data, but rather approximations to the central portions of the profiles. The G160M XD profiles are the sharpest, with a Gaussian $\sigma$ of 2.1 pixels for FUVA and 2.6 pixels for FUVB, as compared to G130M, where the corresponding widths are 4.9 pixels for FUVA and 5.7 pixels for...
FUVB. G140L shows narrow XD profiles with $\sigma=3.0$ pixels for FUV A and 4.0 pixels for FUVB, but with much lower S/N in channel FUVB (where the throughput is much lower).

In Figure 7, we compare the normalized XD profiles between LP2 and LP3. The LP2 profiles were determined in an identical manner, except a linear offset was applied to each one to bring the profile centroid into alignment with the LP3 profiles (the size of each offset is annotated on the panels). For the G140L grating, the FUV A profiles are comparable in shape. For the G160M grating, there is no evident difference between the LP2 and LP3 profiles. However, for G130M, there is a clear difference, with the LP3 profile showing a pronounced shoulder on the low y-pixel side of the detector, which is much weaker in the LP2 data. This shoulder raises the overall width of the G130M XD profile at LP3.

Finally, we compared the LP3 XD profiles between the BOA and PSA. Observations of WD0308–565 for G130M and G140L, and GD71 for G160M were used for the PSA XD profiles, taken from Program 13932, *Third COS FUV Lifetime Position: Cross-Dispersion Profiles, Flux, and Flat-Field Calibration*. The PSA profiles were constructed in an identical manner as the BOA profiles (i.e., using the corrtag files). This comparison is shown (for FUV A data) in Figure 8, in both linear and logarithmic scales. For G160M, the PSA shows a narrower XD profile, and in particular there is more light in the wings of the BOA profile, as shown in the logarithmic plot. When more than 10 pixels away from the profile centroid, the BOA profile is higher than the PSA profile at the $\sim 0.1\%$ level. For G130M, the BOA and PSA profiles are very similar on the high y-pixel side (toward the top of the detector), but there is a marked difference at low y-pixels, in that the BOA profile shows light (at 0.1% of peak flux) down to $\approx 50$ pixels below the profile centroid, whereas the PSA profile only extends down to $\approx 30$ pixels. For both the G130M and G160M cases, the difference does not appear to be due to a lack of light in the wings – if the profile had recovered to the background levels, it would not show a gradient with y-pixel. Therefore the additional contribution in the BOA profiles can be attributed to scattered light. For G140L, the BOA has a more extended wing than the PSA at low y-pixels, as for G130M, although the wings are noisier.
Figure 6. BOA XD profiles at LP3 for six settings. The XD profiles (in black) are formed by collapsing each 2D flat-fielded image in XFULL/YCORR space along the dispersion (X) direction. Dashed red lines show single-component Gaussian fits to the data; the centroid ($y_0$) and width ($\sigma$) of these fits are annotated on each panel.
Figure 7. Comparison of normalized BOA XD profiles between LP2 (red) and LP3 (black), where a linear offset has been applied to the LP2 profiles to bring the centroids into alignment with the LP3 profiles. The magnitude of this offset is annotated on the panel. The G140L/FUVB profile is noisy because of the low throughput of the G140L grating at low wavelengths.
Figure 8. Comparison of normalized BOA (blue solid line) and PSA (red dashed line) cross-dispersion (XD) profiles at LP3 for three grating/cenwave settings (all from the FUV A channel). The left column shows the profiles on a linear scale and the right column shows them on a logarithmic scale to highlight the structure in the wings.

6. Conclusions

Based on the data taken under the LCAL4 program, the BOA is operating successfully at LP3. The XD profiles and flux calibration are comparable to those taken with the BOA at LP2. However, the spectral resolution with G130M has decreased from $d\lambda=0.14$ Å (FWHM) at LP2 to 0.21–0.22 Å at LP3, corresponding to a change in resolving power from $R \approx 9000$ to $\approx 5800$. These findings are verified at two separate wavelengths (1260 and 1193 Å). For G160M, we measure a LP3 resolving power with the BOA of $d\lambda=0.10–0.13$ Å ($R=11900–15000$) at 1548 Å, which we show is similar to the LP2 resolving power with this grating, though further observations of sources with narrow interstellar or photospheric lines in the G160M bandpass are needed to refine this measurement.
Acknowledgments

The authors thank the COS/STIS Instrument Team for useful comments. We are particularly grateful to Paule Sonnentrucker for her review and to Steve Penton for suggestions.

References