Preliminary Characterization of the On-Orbit Line Spread Function of COS

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We present a preliminary analysis of the line spread function (LSF) of the Cosmic Origins Spectrograph (COS) using FUV and NUV stellar spectra acquired during the SM4 Servicing Mission Observatory Verification (SMOV). Our results indicate that the on-orbit shape of the COS LSF with the HST optical telescope assembly (OTA) deviates from the profile measured in ground testing due to the appearance of broad non-Gaussian wings. The wings are caused by mid-frequency wave-front errors (MFWFEs) that are produced by the zonal (polishing) errors on the HST primary and secondary mirrors; these errors could not be simulated during ground testing. The MFWFE effects are particularly noticeable in the FUV. While the pre-launch LSF is well described by a Gaussian, the on-orbit LSF has up to 40% of its total power distributed in non-Gaussian wings. The power in these wings is largest at the shortest wavelengths covered by the COS medium-resolution gratings (~ 1150 Å). The effect decreases with increasing wavelength but has a non-negligible effect on encircled energies even at the longest wavelengths. Optical models incorporating the MFWFE effects into the LSF have been calculated for the whole spectral range covered by the FUV and NUV medium-resolution gratings. We show that for the FUV, the convolution of these model LSFs with high-resolution STIS echelle spectra yields an excellent match to the on-orbit COS spectra of the same targets. The model LSFs are available online and can be used by COS observers to assess the impact of the MFWFE broadening on their COS spectra. We address the impact of the on-orbit LSF on various types of COS scientific investigations.

Introduction

The Cosmic Origins Spectrograph (COS) was installed during the most recent servicing mission of the Hubble Space Telescope (SM4) and is the most sensitive ultraviolet spectrograph flown to date. This is particularly true for the far ultraviolet channel of the instrument, which is 10 to 30 times more sensitive than STIS. With its medium-resolution gratings (G130M and G160M, covering 1150 Å – 1800 Å) this channel was designed to reach a spectroscopic resolving power of at least 20,000 (15 km s^{-1}) across 80% of its passband (STE-63, 2004). The COS near ultraviolet channel was designed to cover the 1750 Å – 3200 Å spectral range with a sensitivity 2-3 times larger than STIS. It utilizes medium-resolution gratings (G185M, G225M and G285M) with similar spectroscopic resolving power requirements to the FUV.

Thermal vacuum measurements showed that for the G130M and G160M FUV gratings the LSF of an unresolved line was well approximated by a Gaussian profile with a FWHM of approximately 6.5 pixels, corresponding to $\Delta\lambda$ = 0.065 Å at 1300 Å and $\Delta\lambda$ = 0.079 Å at 1600 Å. The LSFs of the NUV gratings are expected to have broad wings due to the response of the MAMA detector in the NUV (similar to what is seen for the STIS MAMA LSFs). Analysis of the NUV thermal vacuum data was performed by fitting a Gaussian to the core of the LSF; this yielded FWHM widths of about 3 pixels, or $\Delta\lambda$ ~ 0.11 Å at the default central wavelengths of the G185M, G225M and G285M gratings. Measured resolving powers were $R \approx$ 16,000-20,000 for the G185M grating and $R \approx$ 20,000-24,000 for the G225M and G285M gratings.

On-Orbit Results

The COS LSF measured on-orbit with the HST OTA has been found to deviate from the profile measured in TV06. As shown in this report, analysis of stellar spectra obtained during SMOV indicates that the *HST OTA produces non-Gaussian wings in the on-orbit COS LSF, and both broadens the core of the profile and lowers its amplitude*. The wings are a consequence of *mid-frequency wavefront errors* (MFWFEs), produced by zonal (polishing) errors on the HST optical telescope assembly (OTA). These features were mapped via a phase-retrieval analysis of WFPC2 imagery by Krist & Burrows (1995; see **Figure 1**). However, the MFWFEs of the HST OTA are not included in RAS/Cal, and are not corrected by the optics of COS or any other HST instrument. Therefore, the beam entering COS on-orbit is slightly different from the beam delivered by RAS/Cal during thermal vacuum testing. The effects of the MFWFEs were not included in pre-launch modeling of the COS LSF.

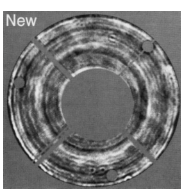

Figure 1. *Map of the zonal (polishing) errors on the HST primary mirror (reproduced from Krist & Burrows 1995). The WFPC2 and HST OTA obscurations are superimposed.*

Although the COS FUV channel is more sensitive between 1150 Å and 1800 Å than any previous spectrograph flown to date and is producing science spectra of exquisite quality, the MFWFEs from the HST OTA result in an LSF with a broader core and non-Gaussian wings that impacts the spectral resolving power of the spectrograph. This in turn reduces the detectability of faint, narrow spectral features, as compared to the Gaussian LSF derived from TV06 data. The MFWFE effect is most pronounced at shortest wavelengths (**Figure 2; Table 1**).

While the effects of the MFWFEs on the LSF decrease with increasing wavelength, they remain significant for both the FUV and NUV channels. The NUV LSF also exhibits non-Gaussian wings, but the contribution of the MFWFEs to these wings is smaller than for the FUV, particularly for λ > 2500 Å. The main contributor to the non-Gaussian wings at the longer NUV wavelengths is the blurring produced by the MAMA detector point response function (a feature also present in the STIS MAMA detectors).

We have produced optical models of the COS LSF, taking into account the MFWFEs (as well as the appropriate detector responses). We find that the COS spectra are reproduced very well when high-resolution STIS spectra of the same targets are convolved with our model LSFs. We have made these model LSFs available to the astronomical community for use in analyzing COS science spectra and for the planning of future COS observations. They can be found at:

http://www.stsci.edu/hst/cos/performance/spectral_resolution/

LSF Models

We computed model LSFs for the COS gratings from the expected aberration content of the COS + HST OTA system, OTA pupil geometry, OTA MFWFEs as determined by Krist & Burrows (1995), and estimates of the point response function of the detectors.

The LSFs for the FUV channel were produced for each grating by first matching monochromatic images generated by a Code V optical model of the COS + HST OTA system to emission line images from thermal vacuum testing with the RAS/Cal stimulus. In particular, a mean detector-induced blur kernel was estimated by matching a suite of images over the spectrum. The model was then used to generate Zernike aberration coefficients, which, together with the OTA pupil function and the MFWFEs, were employed to compute the expected PSF at a number of wavelengths for each grating. The PSFs were then convolved with the estimated detector blur kernel and integrated in the cross-dispersion direction to form the LSFs. **Figure 2** shows that these FUV LSFs are characterized by prominent wings, broader cores and lower central peaks than the nearly Gaussian LSFs computed without the OTA MFWFEs.

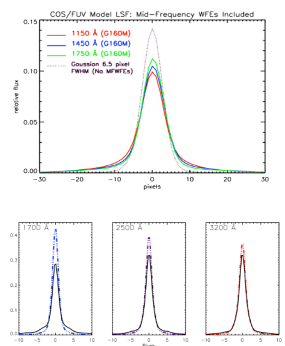

Figure 2. Top: *Calculated LSFs for the COS FUV medium-resolution gratings. Models inlcuding the effects of the mid-frequency wavefront errors are shown in solid. The dotted line shows a Gaussian LSF with a 6.5 pixel FWHM (the nominal prediction from ground testing, which did not include the wavefront errors).* Bottom: *same models, but for the NUV channel. Note the presence of non-Gaussian wings even in the absence of the mid-frequency errors, induced by the response of the MAMA NUV detector.*

We also produced model LSFs for the COS NUV medium-resolution gratings that incorporate MFWFEs. Since all the NUV gratings are planar and are used with a collimated beam, the NUV optical models assume no variation between gratings or central wavelength settings. While the optical design of the NUV channel is very well corrected and contains inconsequential residual aberrations, small manufacturing and alignment errors are certain to exist, both internally and with respect to the OTA. We estimated these effects, along with a typical OTA "breathing" focus offset, by including 15 nm RMS WFEs (all in focus) in addition to the OTA MFWFEs. We also convolved the resulting PSFs with a MAMA detector point response function (as taken from STIS NUV MAMA measurements at Ball Aerospace), These detector wings would of course have also been present during ground testing. The relative contributions of the wings from the MAMA detector and the wings produced by the MFWFEs are illustrated in the bottom panel of **Figure 2**, which compares model NUV LSFs with and without the MFWFEs included.

LSF Model	G130M	G160M	G185M	G225M	G285M
No WFEs	76%	76%	64%	63%	61%
With WFEs (λ - avg)	59%	63%	49%	51%	53%

Table 1. The fraction of the flux enclosed within the FWHM of the model COS LSFs. Values are shown for the medium resolution gratings both for cases where mid-frequency wavefront errors are not included (top) and for cases where they are included (bottom). Note that the flux enclosed within the FWHM for the FUV model without MFWFEs is simply that of a Gaussian, 24%.

Comparison to On-Orbit COS Data

In **Figure 3** we compare the COS spectrum from SMOV (black solid line) of the O9 Ib star Sk 155 in the LMC with a STIS E140H high resolution spectrum (R ~ 114,000) that has been convolved with an R = 20,000 Gaussian LSF (blue dashed line). Also shown in **Figure 3** is the STIS spectrum convolved with an MFWFE LSF model appropriate for the wavelengths displayed (solid red line). *This figure clearly shows that the rounded, filled-in absorption cores are not properly reproduced by an R = 20,000 Gaussian LSF, which systematically underpredicts the flux at line centers and produces more boxy shapes for the broad, saturated absorption lines than is observed.*

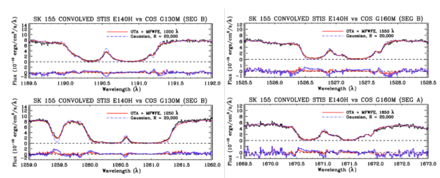

Figure 3. *Left: Closeup views of prominent absorption features in the COS G130M (Segment B) spectrum of Sk 155. The STIS E140H spectrum convolved with an R = 20,000 Gaussian is overplotted in blue, while in red it is presented the convolution of the STIS data with the MFWFE LSF model appropriate to the wavelength range shown. The RMS residuals to the fits are (for an MFWFE LSF and an R = 20,000 Gaussian, respectively) RMS = (3.3E-14; 5.1E-14) at 1190 Å and (3.4E-14; 5.0E-14) at 1260 Å (RMS units are ergs/cm^2/s/ Å). Right: Same as left panel, but for G160M data from Segment B of COS. The RMS residuals to the fits are RMS (for MFWFE LSF and R=20,000 Gaussian, respectively) = (2.4E-14; 3.4E-14) at 1527 Å and (3.1E-14; 3.8E-14) at 1671 Å. (RMS units are ergs/cm^2/s/ Å).*

Impact of the On-Orbit LSF on COS Science

Some of the COS observations that could potentially be affected by the newly characterized on-orbit LSF are as follows:

- Science observations intending to use the full resolution of the FUV G130M and G160M and the NUV G185M medium-resolution gratings will be most seriously affected, (though to some extent the following caveats will apply to data obtained with all COS gratings):

- At a given signal-to-noise, weak, narrow features (b < 35 km s-1) will be more difficult to detect.
- Closely spaced spectral features may blend and become more difficult to isolate kine-matically.
- Analysis of saturated lines will require full consideration of the LSF.
- Studies requiring measurement of accurate line profile shapes will also require full consideration of the LSF.
- Spectral purity will be reduced, resulting in decreased contrast between line cores and wings.

- Science observations that are expected to be less affected by the MFWFEs include:

- Observations of broad-lines (b > 35 km s^{-1}).
- Measurements of continuum fluxes or SEDs.
- UV observations with the G225M and G285M gratings having sufficient S/N to overcome slightly reduced spectral purity should recover the full expected resolution.
- For FUV G140L observations, the LSF is broadened at a level comparable to that of the G130M and G160M gratings. However, we expect that most science programs critically depending on accurate measurement of line profiles would use the G130M and/or G160M gratings rather than the G140L. Therefore, we anticipate that most G140L science programs will be minimally affected.
- For NUV G230L observations, the effects should be similar to that of the NUV medium-resolution gratings at comparable wavelengths.

References

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