The ACS/WFC G800L Grism: I. Long-term Stability

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February 28, 2019

Abstract

We have obtained new ACS/WFC G800L grism observations of the Wolf-Rayet star WR96, a wavelength calibration target, in HST Cycle 25 (PID: 15401) to evaluate differences, if any, in the basic grism properties compared to the previous calibration data. The past calibration efforts for the ACS/WFC G800L grism were based on observations from 2003. In this ISR, we compare these new observations with the previous (pre-SM4) results to validate various basic grism properties: the length and separation of different grism orders, the X/Y shift between the object position in the direct image and the position of the grism 0th order, the spectral tilt, and the wavelength calibration. Our results qualitatively agree with the previous measurements, and confirm that the wavelength calibration of the ACS/WFC G800L grism is consistent within 1 pixel (∼40Å). In an upcoming ISR, we will use all the existing WR96 ACS/WFC grism data along with a new and improved data analysis technique to refine the wavelength calibration of the ACS/WFC G800L grism.

1. Introduction

The HST/Advanced Camera for Surveys (ACS) Wide Field Channel (WFC) has a 3.4′ × 3.4′ field of view at a spatial resolution of 0.05″ per pixel and is equipped with the G800L grism, a low resolution slitless spectroscopy mode, covering a spectral range of 5500Å to 10000Å. The ACS/WFC grism resolving power is ∼100, and the dispersion is nearly linear at ∼40Å per pixel in the first order [Pasquali et al. 2006].
The ACS/WFC G800L grism has been extensively used since its inception in 2002. Large extragalactic surveys such as GRAPES (Pirzkal et al. 2004), PEARLS (Pirzkal et al. 2013), 3D-HST (Momcheva et al. 2016), GLASS (Treu et al. 2015), and FIGS (Pirzkal et al. 2017) have obtained G800L observations and are using these data to investigate astrophysical objects such as M/L/T-type stars, supernovae, emission line galaxies, passive galaxies, and high-redshift Lyman break/Lyman-\(\alpha\) galaxies.

The ST-ECF (Space Telescope-European Coordinating Facility) supported the spectroscopic modes of ACS until 2010. The existing calibrations (wavelength, flux, trace measurements) of the ACS/WFC G800L grism are all based on the data taken in 2002–2003 (Pasquali et al. 2003, 2006), and the last analysis of these data was performed by Kuntschner et al. (2008). This astrophysically important spectroscopic observing mode has been regularly used by the astronomical community throughout the lifetime of the ACS instrument. Unlike HST’s WFC3/IR grisms, which have been monitored on a yearly basis, G800L calibrations have not been revisited since 2008. To rectify this situation, we have conducted a pilot investigation to validate basic grism properties including the wavelength calibration of the ACS/WFC G800L grism.

2. New observations of WR96

We obtained new 1-orbit data in HST Cycle 25 (PID: 15401) of a calibrating target, the Wolf-Rayet star WR96 (J2000 RA: 17:36:24.2, DEC: –32:54:29.0), using the ACS/WFC G800L grism in 2018. These observations are used to compare basic grism properties of the ACS/WFC grism with the prior observations in 2002-2003. We have chosen this particular target because it is a bright point source with strong emission lines and hence an ideal object for grism calibrations as discussed in detail by Pasquali et al. (2001) and Larsen et al. (2005). To summarize the main points, a calibrating target is best suited for the grism calibrations if, (a) the target is bright enough to require reasonably short exposure times, (b) the target spectra contain a significant number of unblended emission lines and/or have a high resolution reference spectrum from the ground, (c) the target is isolated enough to avoid contamination from nearby objects, and (d) the target is compact enough to allow for accurate determination of the dispersion and wavelength zero points. The star WR96 satisfies all of these criteria. Additionally, WR96 has been observed with the ACS/WFC G800L grism during the first few cycles immediately after the ACS was installed in 2002 (i.e., between 2002 and 2004), so it is a perfect target to compare pre- and post-SM4 data.

The slitless spectroscopic observations rely on a pair of direct and grism images because the zero point of the grism wavelength solution is set by the position of the object in the direct image. The field of view of the ACS instrument suffers from significant geometric distortion (e.g., Kozhurina-Platais et al. 2015), and the grism is not perfectly aligned with the detector, so these two effects introduce field dependence in various grism properties. Consequently, the calibration targets have to be observed at different positions across the ACS/WFC chips in order to properly account for this field dependence. We observed WR96 for 20 secs in G800L filter (grism image) and 1 sec in F775W filter (direct image) at 3 different positions on the ACS/WFC chips (Figure 1) to verify calibrations of the ACS/WFC G800L grism.
Figure 1: New observations of WR96. The red circles in the upper-left panel show three different positions on the ACS/WFC detectors for which new observations of WR96 were obtained. The black points (squares and triangles) are observations from the 2002-2003 calibration campaign. The upper-right panel shows the DSS image of WR96, while the bottom panel shows the grism G800L image with the respective orders labelled and its corresponding direct F775W image for WR96.

These exposure times are same as the 2002-2003 observations. The three observing positions are: the center of chip 1 or WFC1 (WFC1 aperture), the center of chip 2 or WFC2 (WFC2 aperture), and the center of the WFC Amp A 2K subarray on chip 1 (WFC1A-2K subarray aperture). The WFC1 aperture at the center of WFC1 will allow us to compare these new observations with the existing observations of the same star at the same position. The full detector readout for two apertures (WFC1 and WFC2) at chip centers will allow us to observe other stars/compact objects in the ACS field of view, which will be important to perform a check on the trace calibration in the future. The upper-left panel of Figure 1 shows three different positions on the ACS/WFC detectors for which new observations of WR96 were obtained, as denoted by red circles. The black points (squares and triangles) are observations from the 2002-2003 calibration campaign. The upper-right panel shows the DSS image of WR96, while the bottom panel shows the grism G800L image with the
respective orders labelled and its corresponding direct F775W image of WR96. For the purpose of validating basic grism properties in this ISR, we have used new data from two positions only – the WFC1 aperture and the WFC2 aperture. Currently, the ACS/WFC grism subarray observations are not fully supported by the ACS/WFC grism data reduction software, aXe1 (Kümmel et al. 2009), so such observations require additional steps in data processing (e.g., embedding the subarrays in a blank full frame image). Therefore, the data from the WFC1A-2K subarray aperture will be included in a future ISR where we will perform detailed analysis for the wavelength calibration of the ACS/WFC G800L grism using all the archival subarray data.

3. The ACS/WFC G800L grism properties

The raw/flat fielded ACS/WFC grism images can be used to measure a number of grism properties including the length of different grism orders, the separation of various grism orders from the 0th order, the separation of the grism 0th order from the direct image, and the tilt of the spectrum. These quantities are very crucial to find and trace spectra as well as to define the size of the extraction aperture along the dispersion axis. The goal of this ISR is to measure these quantities from the new HST Cycle 25 observations and compare those to 2002-2003 measurements. We have used pipeline generated FLC (CTE-corrected flat-fielded) files for the current analysis. The short grism exposures have low background and are prone to CTE losses. The CTE trails are perpendicular to the dispersion axis (which is close to detector X-axis) and will primarily affect the flux calibration of the grism spectra, so for the current analysis, CTE-corrected FLC data are adequate.

3.1. The length and separation of different grism orders

The flat fielded ACS/WFC grism spectra of WR96 in ±1st and ±2nd grism orders obtained from the 2018 observations are qualitatively very similar to spectra obtained from the 2003 observations as shown in Figure 2. These spectra show strong emission line features that are vital for the wavelength calibration of the ACS/WFC G800L grism (more details on this topic are presented in Section 3.3).

In order to measure the length of each grism order in pixels, a threshold is needed to distinguish between pixels from the target spectra and pixels from the background. We estimated the background using the Python Photutils2 package, which provides a convenience function, make_source_mask, for creating source masks. It uses sigma-clipped statistics as the first estimate of the background and noise levels for the source detection. Sources are then identified using image segmentation. Finally, the source masks are dilated to mask more extended regions around the detected sources. Once the background was estimated using Photutils, the threshold was fixed at a 3σ level above the background. For proper comparison, this 3σ threshold level is identical to the 2003 threshold cut. Pixels whose counts are larger than this threshold are assigned to different orders of the target spectrum. We

1http://axe-info.stsci.edu
2https://photutils.readthedocs.io/
measured the length of ±1\textsuperscript{st} and ±2\textsuperscript{nd} grism orders on WFC1 (WFC1 aperture) as well as on WFC2 (WFC2 aperture). The average measurement of lengths (in pixels) for each order is shown in Table\[1\]. In principal, the ±2\textsuperscript{nd} order should be about twice as long as the ±1\textsuperscript{st} order, but the very low sensitivity of the grism 2\textsuperscript{nd} orders at longer wavelengths prevents the detection of this order at \(\lambda > 8000\text{Å}\).

The new measurements, obtained from 2018 observations, are comparable to the 2003 measurements done by Pasquali et al. (2003). The small difference in pixel lengths could be due to the difference in the background estimate and hence, the threshold. To understand measurement differences, we estimated lengths of various grism orders from 2003 data using our approach, and found excellent agreement (within uncertainties) between our measurements. The results are shown in Table\[1\]. It is worth noting that the 2003 measurements are averaged over 10 different positions/pointings (5 per chip) compared to only two positions/pointings (1 per chip) for the new observations. Similar consistency is also seen in the measurement of length for the ±3\textsuperscript{rd} grism order, which has much lower S/N compared
to first two orders. The grism 0\textsuperscript{th} order is dispersed over 27.0±1.0 pixels, and the FWHM is 3.9±0.2 pixels. These values are similar (within 3 pixels) to the previous measurements \cite{Pasquali03}, which obtained a dispersion of 23.0±0.8 pixels and FWHM of 4.4±0.3 pixels for the grism 0\textsuperscript{th} order. For reference, a point source is dispersed over ~15 pixels, and has a FWHM of ~2 pixels. This is the main reason why the grism 0\textsuperscript{th} order is not used for the wavelength zeropoint.

We also measured the separation of various grism orders from the grism 0\textsuperscript{th} order. The separation is measured along the image X-axis and indicates the distance between the center of the grism 0\textsuperscript{th} order and the first pixel of the n\textsuperscript{th} order which is 3\(\sigma\) above the background. To reiterate, the averaged 2003 values were obtained from multiple positions on the ACS WFC detector, while 2018 values are based on two positions only. The average measurement of the separation between various grism orders from \cite{Pasquali03}, as well as individual measurements from 2018 data are shown in Table 2. For comparison, we also measured the separation between various grism orders from 2003 observation at the center of WFC1. The 2003 and 2018 measurements at the center of WFC1 agrees very well (within 3 pixels) as shown in Table 2. Just based on two measurements from 2018 data, we see a likely trend in the separation of various grism orders such that the separation values are lower for WFC2 compared to WFC1.

<table>
<thead>
<tr>
<th>Data</th>
<th>(0\textsuperscript{th} \rightarrow +1\textsuperscript{st})</th>
<th>(0\textsuperscript{th} \rightarrow +2\textsuperscript{nd})</th>
<th>(0\textsuperscript{th} \rightarrow -1\textsuperscript{st})</th>
<th>(0\textsuperscript{th} \rightarrow -2\textsuperscript{nd})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pixels</td>
<td>pixels</td>
<td>pixels</td>
<td>pixels</td>
</tr>
<tr>
<td>2003\textsuperscript{a}</td>
<td>93</td>
<td>251</td>
<td>−122</td>
<td>−247</td>
</tr>
<tr>
<td>2003 (WFC1)\textsuperscript{b}</td>
<td>95</td>
<td>265</td>
<td>−135</td>
<td>−270</td>
</tr>
<tr>
<td>2018 (WFC1)</td>
<td>95</td>
<td>262</td>
<td>−132</td>
<td>−268</td>
</tr>
<tr>
<td>2018 (WFC2)</td>
<td>93</td>
<td>252</td>
<td>−126</td>
<td>−256</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Average measurements taken from \cite{Pasquali03}.

\textsuperscript{b}Our measurements from 2003 data.

### 3.2. The X/Y shift and spectral tilt measurements

The ACS/WFC grism spectra are slightly tilted with respect to the image X-axis. To locate the spectrum in the grism image, we need (a) the difference in (X,Y) coordinates between the object position in the direct image and the position of the grism 0\textsuperscript{th} order, and (b) an additional term that takes care of the spectral tilt. We measured the separation (in pixels) between the position of the grism 0\textsuperscript{th} order and the object position on the direct image at the center of the two chips, as shown in Figure 3 and the comparison of these measurements with 2003 values is shown in Table 3.

The separation between the the object position in the direct image and the position of the grism 0\textsuperscript{th} order at the center of WFC1 is very similar (within 1 pixel) to the 2003
Figure 3: Measurement of the (X,Y) shift, which is the separation between the position of the grism 0\textsuperscript{th} order and the position of the object in the direct image, at the center of WFC1 and WFC2. The measurement, and the value at the center of WFC2 is in accordance with the observed trend (as shown in Figure 4 of [Pasquali et al. (2003)]), which shows that the absolute value of the shifts (X,Y) is decreasing as we move vertically down from the center of WFC1 to the center of WFC2.

Table 3: (X, Y) shifts — Separation (in pixels) between the object position in the direct image and the position of the grism 0\textsuperscript{th} order at the center of WFC1 and WFC2.

<table>
<thead>
<tr>
<th>Data</th>
<th>0\textsuperscript{th} \rightarrow Direct</th>
<th>0\textsuperscript{th} \rightarrow Direct</th>
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<tbody>
<tr>
<td></td>
<td>WFC1</td>
<td>WFC2</td>
</tr>
<tr>
<td></td>
<td>X pixels</td>
<td>Y pixels</td>
</tr>
<tr>
<td>2003\textsuperscript{a}</td>
<td>117.3</td>
<td>$-4.2$</td>
</tr>
<tr>
<td>2018</td>
<td>116.5</td>
<td>$-4.5$</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Measurements taken from [Pasquali et al. (2003)].

To measure the spectral tilt, we obtained (X,Y) coordinates of the knots/emission line peaks along the whole spectrum (from −3\textsuperscript{rd} or +3\textsuperscript{rd} order) and plotted them in the X-Y plane as shown in Figure 4. These data points were fitted with a first order polynomial (a line) to obtain the slope of the spectrum with respect to the X-axis, which is the direction of the dispersion axis. For proper comparison, this measurement approach is identical to the one followed by [Pasquali et al. (2003)].

As shown in the left panel of Figure 4, the spectrum tilt at the center of WFC1 is $-2.261 \pm 0.025$, and $-1.660 \pm 0.012$ at the center of WFC2. The right panel of Figure 4 shows a
Figure 4: [Left] The spectral tilt measurement approach showing plotted data points and the linear fit with its corresponding slope. [Right] Figure reproduced from Pasquali et al. (2003), showing field dependence of the spectral tilt. The new measurements based on 2018 data are shown in red and represent measurements at the current locations of the WFC1 and WFC2 apertures.

The figure taken from Pasquali et al. (2003) that sketches the field dependence of the spectral tilt. The new measurement of the spectral tilt at the center of WFC1, $-2.261 \pm 0.025$, is identical (within uncertainties) to the 2003 measurement ($-2.250 \pm 0.012$) of the spectral tilt at the center of the chip 1. Moreover, the 2018 spectral tilt measurement at the center of WFC2 is in accordance with the 2003 trend shown in the right panel of Figure 4, where the spectral tilt is decreasing as we move vertically down from the center of WFC1 to the center of WFC2. The overall variation of the spectral tilt as a function of position on the chip is dictated by the geometric distortion of the ACS.

3.3. The ACS/WFC G800L grism wavelength calibration

Larsen et al. (2005) performed detailed analysis to measure the wavelength calibration of the ACS/WFC G800L grism by combining all the data available at that time. These measurements of the wavelength calibration are currently being used during the ACS/WFC G800L grism data reduction process because this was the last study done to revise/improve wavelength calibration for the ACS/WFC G800L grism. The results from the Larsen et al. (2005) analysis show that the wavelength calibration of the ACS/WFC grism is consistent within 1 pixel ($\sim 40$ Å) when compared to the initial calibration done in 2003 (Pasquali et al. 2003). The main goal of this ISR is to verify the wavelength calibration by comparing observed emission line wavelengths in the new WR96 data with the reference/expected line wavelengths obtained from the high resolution ground based spectra (Pasquali et al. 2006).
The 2018 ACS/WFC G800L grism data of WR96, obtained at the center of WFC1 and WFC2, were reduced using the spectral extraction software, aXe (Kümmel et al. 2009), which uses configuration files that are based on the wavelength calibration solution of Larsen et al. (2005). The resulting spectra of WR96 (green) are shown in Figure 5 with some prominent features marked by vertical red lines. Figure 5 also shows high resolution ground-based spectrum of WR96 in black. This high resolution spectrum is convolved with the ACS PSF (FWHM ~ 2.5 pixels or ~ 100 Å) and is shown in blue. By measuring the centroids of the various emission line features (red dashed lines) and comparing with their expected wavelengths (red solid lines), which are based on high resolution ground-based spectra (Pasquali et al. 2006), we generally find good agreement within a maximum absolute difference of about 40 Å. An exact match between the observed and expected wavelengths for all emission lines is not possible since many of these spectral features seen in the grism spectrum are blended because of lower resolution of these data, and are clearly seen in high resolution ground-based spectrum (black) and PSF convolved spectrum (blue). Figure 5 shows vertical grey shaded regions adjacent to the expected emission line wavelengths, which is ± 40 Å in width and corresponds to the current accuracy of the wavelength calibration. For most emission lines, both wavelengths (observed and expected) lie within this shaded region, and the difference between these wavelengths is within ~ 40 Å (~ 1 pixel) as expected based on prior wavelength calibrations (Pasquali et al. 2003; Larsen et al. 2005). This comparison suggests that the wavelength calibration of the ACS/WFC G800L grism is accurate to better than 1 pixel.

4. Summary and future work

We have obtained new ACS/WFC G800L grism observations of the calibration Wolf-Rayet star, WR96, at three different positions on the ACS/WFC detector to verify the basic grism properties including the length and separation of different grism orders, the X/Y shift and spectral tilt measurements, and the wavelength calibration. Our measurements, based on the 2018 grism observations, qualitatively agrees with the previous analysis done between 2003 and 2005. The 2018 grism data covers only three spatial positions on the ACS/WFC detector which is inadequate for detailed analysis of the wavelength calibration as the solution varies across the detector because of geometric distortion. In an ongoing work, we are combining all the existing ACS/WFC G800L grism data of WR96, spread over the full ACS/WFC detector, to refine wavelength calibration for the ACS/WFC G800L grism. Our goal is to combine the re-reduced archival WR96 data with the new and improved wavelength calibration technique, which has been successfully applied to the WFC3/IR grism calibration by Pirzkal et al. (2016), to update the wavelength calibration of the ACS/WFC G800L grism. The performance of the ACS/WFC G800L grism has been reassuringly stable over the lifetime of the ACS. We strongly recommend that the community take full advantage of the G800L grism, a low resolution slitless spectroscopy mode on the ACS/WFC, which is highly sensitive at optical wavelengths and has the unmatched spatial resolution of HST.
Acknowledgement

We would like to thank Ralph Bohlin, Jenna Ryon, Melanie Olaes, and Ray Lucas for their valuable comments that improved the quality of this report. NH would like to thank Søren Larsen for providing the high resolution ground-based spectrum of WR96.

References

- Pirzkal, N., Ryan, R., & Brammer, G. 2016, ISR WFC3-2016-15
Figure 5: Comparison of the observed emission line wavelengths (red dashed lines) in the $+1^{st}$ order spectrum of WR96 (green) on WFC2 [Top] and WFC1 [Bottom] with the reference/expected emission line wavelengths (red solid lines). The high resolution ground-based spectrum (black), and the PSF convolved spectrum (blue) are shown for comparison. The vertical grey shaded regions, which are ±40Å wide from the expected reference wavelengths, corresponds to the current accuracy for the wavelength calibration (~1 pixel or ~40Å) of the ACS/WFC G800L grism [Larsen et al. 2005].