Abstract

We provide the preliminary results of a study on the photometric repeatability of spatial scans of bright, isolated white dwarf stars with the UVIS channel of the Wide Field Camera 3 (WFC3) on the Hubble Space Telescope (HST). We analyze straight-line scans from the first pair of identical orbits of HST program 14878 to assess if sub 0.1% repeatability can be attained with WFC3/UVIS. This study is motivated by the desire to achieve better signal-to-noise in the UVIS contamination and stability monitor, in which observations of standard stars in staring mode have been taken from the installation of WFC3 in 2009 to the present to assess temporal photometric stability. Higher signal to noise in this program would greatly benefit the sensitivity to detect contamination, and to better characterize the observed small throughput drifts over time. We find excellent repeatability between identical visits of program 14878, with sub 0.1% repeatability achieved in most filters. These results support the initiative to transition the staring mode UVIS contamination and photometric stability monitor from staring mode images to spatial scans.
1. Introduction

This report is on preliminary results of the repeatability of high precision photometry using spatial scans of bright, isolated stars with WFC3/UVIS. HST program 14878 (Cycle 24) is a six-orbit program, four of which have been completed and analyzed at the time of this publication. The first visit of this program was an experimental visit intended to test various scan trajectories and choose the optimal scan type for subsequent visits. Of the remaining three completed visits, Visit 02 and Visit 03 are identical in structure. We analyze and compare analogous observations from Visit 02 and Visit 03 to assess the repeatability of spatial scans with WFC3/UVIS.

Spatial scans should have two key advantages over staring mode observations. First, millions of source photons can be collected in a single exposure without saturation by spreading the signal across many pixels of the detector. Second, averaging over hundreds of pixels averages out spatially dependent sources of noise, for example flat field errors, and enables sampling of different pixel phases along the direction of the scan. The typical photometric repeatability of WFC3, as determined by observations of standard stars, is on the order of 1% (Shanahan et al. 2017). With spatial scans from HST program 14878, we aim to achieve 0.1% repeatability, or to show that WFC3 is not capable of this precision with our methods.

By Poisson statistics, achieving 0.1% photometry requires the collection of at least 1,000,000 photons. To achieve this requires careful planning of each observation. The first visit of 14878 was used to test various scan patterns (single line and multi-line scans) that will both achieve the necessary number of photons, and deposit incident flux evenly and not saturate at any point during the scan. (McCullough, 2017) describes in detail the results from the first visit of 14878, in particular the trajectories of multi-lined scans.

For the subsequent five visits of 14878, we have planned observations based on our findings from Visit 01, striving for the best repeatability possible. At the time of this report, data from four of the six total allotted orbits have been acquired and analyzed. Based on the results of Visit 01, we have chosen to use vertical straight line scans rather than boustrophedonic for the remaining visits. This choice was made to simplify the analysis, as cosmic ray rejection and aperture photometry proved to be simpler on straight line scans.

We develop photometry software for the analysis of scanned data. This includes tasks for source finding, cosmic ray masking, background subtraction, and aperture photometry. Measured count rates from identical exposures between Visit 02 and Visit 03, the first pair of identical visits in this program, are compared to one another to determine the limits of photometric repeatability for these scans.

Program 14878 was designed to be the scanning mode counterpart to the UVIS Con-
tamination and Stability Monitor (cycle 24 program 14815). The ultimate application of the results from this study will be used to determine if the staring mode monitor can be transitioned to scanning mode to achieve greater precision, crucial to characterizing temporal changes in throughput. In this established program, periodic observations of the spectrophotometric standard white dwarf stars GD153 and GRW+70D5824 (GRW70) are taken through a key set of UVIS filters, observed from SMOV in 2009 to the present. The consistency of measured countrates indicates the stability of photometric throughput as both a function of time and wavelength; contamination, which would manifest as a decrease in throughput greater in magnitude in UV filters than in visible wavelengths, has not been detected thus far. However, steady declines in throughput ranging from 0.01 to 0.3% per year, greater in the redder filters, have been measured (Shanahan et al. 2017). The mechanism behind these declines is yet understood, though several likely causes (CTE losses, filter degradation, breathing, etc.) have been ruled out. Achieving higher signal to noise in measurements of these standard stars over time will enable better characterization of these drifts.

Like 14815, we image two bright, isolated white dwarf standard stars. The spectra and characteristics of these stars, GRW70 and GD153, are detailed in Table 2. GRW70 is part of the original set of standard stars chosen for HST (Bohlin, 1996) and has been observed periodically since the installation of WFC3 in 2009. This star has also been used as a monitor for other HST instruments including STIS (Stys et al., 2001) and WFPC2 (Whitmore et al., 1996). Recent evidence suggests GRW70 exhibits long-term, low-level variability (Bohlin, R., Landolt, A., 2015). For this reason, beginning in cycle 23, the staring mode monitor began imaging another standard star GD153, with a small number of contemporaneous GRW70 visits to tie results from the new standard back to past monitor data.

1. Data

Several considerations were made in planning program 14878 to obtain the best quality data and approach the desired 0.1% repeatability per exposure. At the time of this publication, four of the six scheduled HST orbits have been completed and analyze. Table 1 outlines the structure of each of these four visits. The first identical visit pair (Visit 02 and Visit 03), the focus of this analysis, imaged the standard white dwarf star GD153 in a subset of UVIS filters. Data were obtained on both CCD chips, and half were post-flashed.

We used the scanning mode capability of the Exposure Time Calculator (ETC), as well as a numerical simulation of scan trajectories (McCullough, 2017) to design program 14878. Several other considerations were made to ensure the best quality data. We looked at various surveys for other objects in the vicinity of our targets to inform any orientation
restrictions to avoid overlapping star trails. Additionally, we updated positions and proper motion values from GAIA to ensure that the source falls on the same pixels consistently visit to visit. Finally, we scan at a prescribed angle to ensure that the star uniformly samples pixel phases along the scan (McCullough & MacKenty, 2012).

To maintain consistency with the staring mode UVIS contamination and photometric stability monitor, we observe the same targets. The spectra and characteristics of these stars, GRW70 and GD153, are detailed in Table 1. We also image in the same set of UVIS filters as this program to be able to tie the scans back to staring mode images: F218W, F225W, F275W, F336W, F438W, F606W and F814W. This set was chosen to obtain comprehensive coverage at shorter wavelengths where contamination effects would be seen, and two longer wavelength control filters to compare to throughput trends in the UV. Additionally, we use the same 512 x 512 pixel corner subarrays near the A and C amplifiers on UVIS1 and UVIS2, respectively. The use of corner subarrays mitigates CTE losses, and reduces overheads so that more exposures may be packed into each orbit.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>GRW70</td>
<td>13h 38m 51.77s +70d 17’ 08.5”</td>
<td>12.77</td>
<td>-0.09</td>
<td>DA3</td>
</tr>
<tr>
<td>GD153</td>
<td>12h 57m 02.37s +22d 01’ 56.0”</td>
<td>13.35</td>
<td>-0.29</td>
<td>DA1</td>
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</table>

Table 1: Spectra and characteristics of our white dwarf spectroscopic standards, GRW70 and GD153. From the HST CALSPEC Calibration Database (http://www.stsci.edu/hst/observatory/crds/calspec.html).
1.1 Visit 01

Visit 01 was an experimental visit used to try various single and multi-lined scan trajectories. Scans were obtained on the UVIS2-C512C-SUB subarray through F218W, F225W, F606W, and F814W. The scan trajectories obtained in Visit 01 are shown in Figure 1. Each image is the 512 x 512 pixel C quadrant subarray in its entirety, with each of the eight unique scan patterns labeled with an integer 0-7. The straight line scans (0) were obtained horizontally. Several variations of multi-line boustrophedonic scan trajectories (1-7) were obtained as well.

Fig. 1.— All scans obtained in Visit 01 (McCullough, 2017). Each unique scan pattern is labeled with an integer 0-7.
1.2 Visits 02, 03, and 11

Despite the excellent agreement of multi-line observations with the simulations, we determined that single line scans are simpler to analyze. In particular, cosmic ray rejection is much simpler and reliable on single-lined scans. For this reason, we chose to use single line scans for each subsequent visit of program 14878. We chose vertical scans, not horizontal scans, to mitigate CTE changes over time, although this was not a critical choice as long as it is consistent thereafter. We use both flashed and unflashed exposures on UVIS2, in case we ever notice a systematic difference, but we lacked the orbits to do both on UVIS1.

Visits 02 and 03 are an identical pair that image GD153. Visit 11 is identical in structure, but observes GRW70. In these visits, we obtain straight line vertical scans in the filters F218W, F225W, F275W, F336W, F438W, F606W, and F814W. For each filter, we obtain one non-post-flashed image in the UVIS1-C512A-SUB subarray. The scan direction is alternated forward-reverse. For each filter, two observations are obtained on the UVIS2-C512C-subarray. The forward direction scan is non-post-flashed, and the reverse scan is post-flashed (level = 12).

2. Analysis

Raw images are calibrated with the IRAF/STSDAS pipeline program CALWF3 version 3.4 (Ryan et al. 2016). CALWF3 applies bias, post-flash (if used), dark image subtraction, flat-fielding and gain conversion to produce science images in units of e⁻. To ensure a common set of up-to-date reference files for calibration, we retrieved data from the Mukulski Archive for Space Telescopes (MAST). Because of small shifts between visits that place the scan on slightly different places near the center of the subarray, we apply the pixel area map (PAM) to all observations before doing photometry.

2.1 Cosmic Ray Rejection

Due to longer exposure times, and the fact that scans spread incident flux over a large area on the detector, the potential for cosmic rays to impact photometry is higher for scanned images than for staring images.

Building upon an IDL routine originally developed for cosmic ray identification in STIS CCD image, we identify pixels affected by cosmic rays using a tactic that relies on unique characteristics of scanned imagery, specifically that each pixel tends to be very similar to
its neighbors in one direction (vertically, parallel to the scan direction) and less so in the perpendicular direction (horizontally). Our simple cosmic-ray analysis treats each column of the image independently of all other columns. After identifying the pixels affected by cosmic ray hits, we interpolate across them with a straight line connecting the two values of the two pixels, the one immediately above and the one immediately below each gap defined by those pixels affected by the cosmic ray. We substitute the interpolated values in the appropriate pixels affected by cosmic rays. The algorithm works very well in the sky region of the image and in the steady-state region of each star trail, but not so well at each end of each star trail. For this reason, we use a vertical median filter near the ends of the trails, where the main identification and interpolation is not as successful.

2.2 Generating source lists

We have developed a simple routine to identify the center of straight-line scans. This software is able to identify the x and y center and orientation (vertical or horizontal) of scans assuming only that they are roughly centered (within roughly 100 pixels) on the subarray. First, the orientation of the scan is determined by looking at the distribution of pixels across both axes. For simplicity, the following discussion will outline the procedure for analyzing a vertically oriented scan.

Fig. 2.— Distribution of mean column value (left) and mean row value (right) in an vertical single line scan.

In single-line vertically oriented scans, the PSF is well characterized by a Gaussian along the x-axis, peaking sharply at the center of the scan and falling off on either side. The left panel of Figure 2 shows the mean column value (e-) against column number, with the Gaussian fit overplotted. The x-coordinate center of the scan is localized by the peak of a Gaussian fitted to the mean pixel value in each column.
Next, we find y-coordinate center of the scan by examining the flux distribution along the y-axis. The image is divided into three parts segments: one middle segment that contains the scan within, and the portions on either side. For each segment, we determine the mean of the row after sigma-clipping the distribution. This allows us to fit the center more accurately by removing the noise introduced by hot pixels. Finally, a step function is fit, the parameters of which are used to identify boundaries of the scan and locate the y-coordinate center (Figure 2).

2.3 Sky subtraction

We define the sky region on vertical scans as all pixels excluding a 10-pixel border around the subarray, and a conservatively large 400 x 75 pixel rectangular aperture around the source center. Within this sky region, we use an iterative sigma clipping routine to remove hot pixels and residual cosmic rays. The sky level and sky RMS are the mean and RMS of this clipped distribution. We subtract the mean sky level from the science array before doing photometry.

2.4 Aperture photometry

We perform aperture photometry on the PAM corrected scans to find sky-subtracted source sums. See Table 3 for an overview of the four rectangular apertures (referred to as apertures α, β, γ, and δ) used in this analysis. The nominal position on the subarray is the same between exposures, but instead of using a fixed aperture, we center on each scan individually to correct for small shifts in the center (x,y) position of each trail between exposures. To do this, using source center coordinates found by the method described in Section 2.1. On sky-subtracted images, the source countrate (e-/s) is defined as the sum of pixels within the aperture divided by the exposure time.

We approximate photometric errors on each measurement by the source Poisson noise, which should dominate other noise terms.

3. Results and discussion

Visits 02 and 03 of program 14878 are identical in structure. By comparing the measured countrates in each filter between visits, we can assess the repeatability of spatial scans with WFC3/UVIS.
<table>
<thead>
<tr>
<th>Visit, Target</th>
<th>Filters</th>
<th>Subarray</th>
<th>Scan type</th>
<th>Post-flash?</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visit 03 GD153</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Identical to Visit 02</td>
</tr>
<tr>
<td>Visit 11 GRW70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Identical to Visit 02 except for the target.</td>
</tr>
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</table>

Table 2: Summary of first four visits of HST program 14878.

<table>
<thead>
<tr>
<th>Aperture Label</th>
<th>Width (pixels)</th>
<th>Length (pixels)</th>
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<tbody>
<tr>
<td>α</td>
<td>16</td>
<td>250</td>
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<tr>
<td>β</td>
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<tr>
<td>δ</td>
<td>70</td>
<td>250</td>
</tr>
</tbody>
</table>

Table 3: Dimensions of the four photometric rectangular apertures (α, β, γ, and δ).
Figure 3 shows the ratio of countrates between Visit 03 and Visit 02 in each filter for the \(\alpha, \beta, \gamma,\) and \(\delta\) rectangular apertures. All observations were obtained on UVIS1 in the corner 512 x 512 pixel subarray near the A readout amplifier. All observations are unflashed, and are scanned alternating forward - reverse. Error bars are the standard error propagation of individual photometric errors. Table 4 reports the data corresponding to Figure 3, with each ratio expressed as the difference from the expected ratio of unity, in units of parts per million (PPM). For each aperture size, we obtain near perfect repeatability in the UV filters. The ratios deviate slightly in the longer wavelength filters but we maintain sub 0.3% repeatability overall. The smallest three apertures exhibit higher precision across all wavelengths than the largest: as seen in table 4, the RMS for all filters used are 932, 980, 993, and 1581 ppm for apertures \(\alpha, \beta, \gamma,\) and \(\delta,\) respectively. This suggests that sky noise pixels become an issue at the largest aperture which encloses the most sky. In future work, we may pursue PSF fitting (to each row of the scan) instead of aperture photometry for more accurate treatment of the background pixels. We see no systematic variation from the expected ratio of unity. The mean difference from unity (averaged over all filters used) in units of ppm are 529, 304, 280 and 332 for apertures \(\alpha, \beta, \gamma,\) and \(\delta,\) respectively.

Figure 4 shows the ratio of Visit 03 countrate to Visit 02 countrate in each filter for the \(\alpha, \beta, \gamma,\) and \(\delta\) rectangular apertures. The data associated with Figure 3 is tabulated in Table 5. All observations were obtained on UVIS2 in the corner 512 x 512 pixel subarray near the C readout amplifier. Points in red are post flashed and scanned in the reverse direction. Points in black were not post flashed and were scanned forward. Error bars are the standard error propagation of individual photometric errors. Post-flashed and non post-flashed measurements (equivalently, forward and reverse direction scans) agree well within 0.1% between visits 02 and 03. Like all UVIS1 observations (Figure 3), we see close to 0.1% repeatability in most filters, and sub 0.3% overall, with no systematic variation from the expected ratio of unity.
Fig. 3.— For each aperture size ($\alpha$, $\beta$, $\gamma$, and $\delta$) the ratio of measured countrate (e- /s) of identical visits 03 and 02, for each filter. All observations of GRW70 were obtained on the UVIS1-C512A-SUB corner subarray, and are not post-flashed. Scan directions alternate forward-reverse between observations.
Fig. 4.— For each aperture size ($\alpha$, $\beta$, $\gamma$, and $\delta$) the ratio of measured countrate (e- /s) of identical visits 03 and 02, for each filter. All observations of GD153 were obtained on the UVIS2-C512C-SUB corner subarray. Points in red are the ratios of reverse-scanned, post-flashed observations. Points in black are the ratios of forward-scanned, non post-flashed observations.
4. Conclusion

In this report, we discuss the considerations taken in planning program 14878, a scanning-mode counterpart to the staring-mode UVIS contamination monitor, and the photometry analysis done on vertical scans of bright, isolated standard stars. We report on the initial results of this repeatability study, comparing the first pair of identical visits. Between Visit 02 and Visit 03, identical visits to GD153, we are able to obtain sub 0.1% repeatability in most filters, with the worst case approaching 0.3%. The excellent agreement between the first identical visit pair is encouraging - we will continue to analyze visit pairs in the remaining orbits of 14878 and if we find similar repeatability between subsequent pairs, we will strongly consider transitioning the staring mode UVIS contamination monitor to spatial scans to achieve higher signal-to-noise.

4. Acknowledgments

We would like to thank Adam Riess for reviewing this text and providing edits and feedback.
Table 4: Tabulated data corresponding to Figure 3. All observations were taken in the UVIS1-C512A-SUB subarray, and are not post-flashed. Ratios are expressed as their difference from the expected ratio of unity, in units of parts per million (ppm), and are listed in the 'Δ (ppm)' column for each aperture. The 'Err' columns are the propagated photometric errors for the ratios, in units of ppm. Listed below for each aperture size are the means and RMS values for the 'Δ (ppm)' for all filters.
Table 5: Tabulated data corresponding to Figure 4. The top group of data are post-flashed, reverse scanned. The bottom group of data are not post-flashed, and are forward scanned. All observations are in the UVIS2-C512C-SUB subarray. Ratios are expressed as their difference from the expected ratio of unity, in units of parts per million (ppm), and are listed in the '∆ (ppm)' column for each aperture. The 'Err' columns are the propagated photometric errors for the ratios, in units of ppm. Listed below for each aperture size are the means and RMS values for the '∆ (ppm)' for all filters.
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