The Internal Flat Fields for WFC3/IR

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July 2, 2015

ABSTRACT

We report on the continuous monitoring of the WFC3/IR internal flat fields and extend previous studies with 2–3 more cycles of data and analyze 1067 frames over a 7 year baseline through all (15) filters. We observe a slight decrease in the mode count rate of the tungsten lamp by $\sim$0.3% yr$^{-1}$ ($1 - 2 e^{-} yr^{-1}$) since cycle 18 (MJD$\sim$55 500: Oct. 31, 2010), which weakly depends on bandpass (with bluer bands decreasing more). We find no evidence for any pixel-to-pixel variations over this same time, which taken together suggests that the tungsten lamp is slowly degrading. Additionally, we identify long-term image persistence with a timescale of $\lesssim$6 days that affects $\sim$60% of our internal flat-field images. This program is currently taking data in Cycle 22 and is expected to continue in future cycles as a front-line monitoring of detector performance, lamp condition, and other anomalous behaviors.

1. Introduction

The Wide-Field Camera 3 (WFC3) is equipped with four tungsten and one deuterium internal lamps designed to monitor the performance of both the IR and UVIS channels. Since the internal flat-fields have a very different beam speed than science observations,
these data are primarily intended to monitor pixel-to-pixel variations, fluctuations in mean count rates, and any new wavelength-dependent effects. This internal flat-field program has been continuously operating since the Servicing Mission Observatory Verification (SMOV) period, and has collected a total of 1067 individual frames through 15 bandpasses, although the majority (66%) are with the five wide filters (F105W, F110W, F125W, F140W, and F160W). In this ISR, we extend the analyses of Baggett (2009), Hilbert (2009), and Dahlen (2013) through existing data (as of Dec. 1, 2014) and to include the medium- and narrow-band filters.

2. Data and Analysis

From the standard on-the-fly processing (OPUS_VER HSTDP 2014-3), we analyze the FLT files generated from CALWF3 (ver 3.1.6, 15-Nov-2013). We analyze all the data from six proposals from SMOV to cycle 22 (IDs: 11915, 12338, 12712, 13098, 13587, and 14029). All of these data were taken with the tungsten lamp. Our analysis proceeds in this fashion:

1. Image statistics: After basic reductions from CALWF3, we normalize each FLT to a mode computed from the pixels which have no data quality flags set (i.e. only the good pixels). We compute the mode in a two-stage process: First we bin the data with width $0.1 \, e^{-s^{-1}}$ and identify the bin with the highest frequency. Second, we compute the $3\sigma$-clipped average for data within $\pm$3 bins of the peak. This procedure is far more reliable at determining the mode count rate, since the pixel distributions are highly non-Gaussian, having some negative skew due to the presence of various artifacts (e.g. wagon wheel, death star, etc.). In Figure 1, we show example pixel distributions for ib9m0kvq from Proposal ID: 11915 through filter F128N. Our clipped-modes (red line) are typically $\sim5\%$ higher than sigma-clipped averages (green line) or median (blue line) estimates as reported in earlier works (Hilbert 2009; Dahlen 2013).

We normalize each frame to its corresponding clipped-mode then median combine various subsets of the data to increase the signal-to-noise, further reject cosmic rays, and highlight the pixel-to-pixel variations. We produce two sets of stacked images: one where we stack all the data for a given filter and one where we stack all the data for a given filter and cycle combination. Hereafter, we will refer to these as the master stack and the cycle stack, respectively.

2. Persistence masking: Although our calculation of the mode for individual frames and the median combining of the normalized images are robust to highly deviant pixels (as will be discussed in more detail in §3), we must reliably mask anomalous pixels
Fig. 1.— Distribution of image pixels. We show the image `ib9m0kviq_flt.fits` from Proposal ID: 11915 for F128N. We show various statistics for all good pixels (i.e. data quality of zero) as red (mode), blue (median), and green (sigma-clipped average) lines. As stated in §2, our calculation of the mode more reliably reproduces the peak in the brightness distribution and is $\sim 5\%$ higher than the averages or medians used in previous works (Hilbert 2009; Dahlen 2013). In the inset, we show the FLT linearly scaled over the same range as the histogram, where the color of image is equal to the color of the histogram. We compute clipped-modes for the 1067 FLTs to normalize each image and identify any trends over the life of the instrument.
from transient signals before investigating any pixel-to-pixel variations with bandpass. While the data-quality arrays identify static bad pixels, we must correct for the worst transient offenders, which is usually image persistence (e.g. Long et al. 2011). The WFC3 team has produced expected persistence images by modeling all WFC3/IR data taken prior (within $\sim$12 h) to a frame of interest, which are currently available through the PERSIST Search Form: [http://archive.stsci.edu/prepds/persist/search.php](http://archive.stsci.edu/prepds/persist/search.php). We begin our persistence masking using these data to flag pixels with persistence signals larger than the typical dark rate ($0.015 e^{-} s^{-1} pix^{-1}$).

3. Refine statistics and persistence masks: Using the nominal first-pass persistence masks, we update the clipped-modes and cycle/master stacks described in step 2. To look for anomalous pixels, we inspect the ratio of a normalized FLT to the master stack (of the same bandpass). Many of the ratio images show excess signals of $\gtrsim$1% clearly showing persistence from exposures $\gtrsim$12 h prior to taking the internal flat (see Figure 2 for an example of residual persistence in the dataset [ibvf27t8q](http://archive.stsci.edu/prepds/persist/search.php)). Therefore we require a more conservative estimate of image persistence; for this we update the persistence masks from step 2 by flagging any pixel that has an integrated flux of $\geq30000 e^{-}$. To mask all offensive cases, we must flag pixels (only including external persistence, i.e. excluding data from our internal flat-field programs) as far back as six days — considerably farther back in time than the current persistence modeling. This appears to be a type of latent persistence that can be triggered by the signal from the internal flat-field itself. One hypothesis is that a low level of persistence becomes frozen within the detector and a high-signal image (such as these flat fields) can subsequently burp or release the residual persistence into the readout (P. McCullough, priv. comm.). This long-term persistence affects $\sim$60% of our internal flat-field images.

4. Scattered light frames: During the visual inspection of the ratio images described in step 2, we flag any image that appears to show residual flux associated with a source off the image edge. In Figure 2, we show the dataset [iaak12lxq](http://archive.stsci.edu/prepds/persist/search.php) that shows a significant excess (with respect to the master stack) from scattered light. This glinting has been observed since SMOV and affects only a minority of our data $\lesssim10\%$, which are predominately in the early cycles.

5. Finalize statistics: We recompute the statistics described in step 2 while ignoring any pixels marked for the persistence (either the standard persistence or our long-term persistence) or scattered light. In Table 1 we catalog the observing properties and image statistics for the 15 bands observed since SMOV.
Fig. 2.— Two examples of residual artifacts for F105W data. Here both images are normalized to the master stack (the top-left panel of Figure 6) to highlight very faint structures. Along the bottom we show the gray-scale colorbar for the scaling of both images. These images show scattered light (left panel, dataset: iaak12lxq) and long-term persistence (right panel, dataset: ibvf27t8q). Although these images were visually identified as problematic, their skewness is considerably higher than “clean” frames. As described in § 2 we mask pixels for persistence and omit frames with significant scattered light.
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†Still in progress.
‡Most common combination (≥90% of the data taken with these settings).
3. Results

The primary goal of this monitoring campaign is to identify any variations in the pixel-to-pixel response of the detector and/or tungsten lamp. In Figures 3-5, we show the clipped-mode count rates as a function of modified Julian date (MJD) since SMOV. The small triangles represent the individual FLTs, color coded for cycle (as described in Figure 3), and large filled circles show the averages for a given cycle. We indicate the times and filters studied by Dahlen (2013) with a gray region in Figure 3 (the medium- and narrow-band filters have not been analyzed since SMOV). We observe a weak decline in the clipped-mode count rates beginning in cycle 18 in all five broadband filters and show the best-fit linear model over this time period with a solid black line. Typically the decay is $\sim 1 \, \text{e}^{-1} \, \text{yr}^{-1}$ or $\sim 0.3\% \, \text{yr}^{-1}$ of the mode count rate; we indicate these values in each panel of the figures. However we must omit steps 2–4 for the medium- and narrow-band filters since there are only two images per cycle for these filters, which are often taken in a few epochs (and each epoch lasts $\sim 1 \, \text{hr}$). Therefore the resulting in the persistence and scattered light signals being nearly identical in both frames and so the stacked data have large regions with no valid pixels. It is important to stress: our calculations of the clipped modes are largely insensitive to the omission of these steps, since the bulk of the pixels are not affected by the residual artifacts. However it is important to flag such deviant pixels when interpreting pixel-to-pixel variations in the filters.

In Figure 6, we show the master stacks (left column) and the ratio of the cycle to master stack for each cycle (right columns) and broadband combination. We have omitted the medium- and narrow-band filters since most of the images are masked for the reasons discussed above. The cyan regions show bad pixels for which no data are available, prominently featuring the death star. In Figure 7, we show the pixel histograms for the images (in the same layout) as in Figure 6 over the same range of brightnesses. As noted in §2, the brightness distribution for the internal flats is highly non-Gaussian (left column of this figure, but now for the master stacks). However the ratio of a given cycle stack to the master is very nearly Gaussian (right columns), suggesting that we have robustly accounted for all the signals present in the internal flats. There remains a very small negative skew (mostly from the wagon wheel region) and a very small positive kurtosis. More importantly however, the standard deviation is typically very small ($\sim 0.2\%$) and scales with $N^{-1/2}$ (where $N$ is the number of images from Table 1), which demonstrates there are not strong pixel-to-pixel variations over time for the broadband data. Again, there are too few valid pixels for the medium and narrowband data to provide similar analysis. Therefore whatever is causing the gentle decrease in the mode count rate with time seen in Figure 3 does not impart a strong pixel-to-pixel variation.
Fig. 3.— Mode count rates for the broad-band filters as a function of modified Julian date (MJD). We color code each cycle SMOV (red), 17 (orange), 18 (yellow), 19 (green), 20 (purple), 21 (blue), and 22 (magenta). The small triangles represent the individual FLT's and the large filled circles show the cycle averages. The gray bar indicates the region of data analyzed by Dahlen (2013). There seems to be a slight decrease in the mode count rate for MJD $\gtrsim 55,500$ (Oct. 31, 2010), as highlighted by the solid black line (a best fit to the individual FLT's). In the upper corner of each panel, we give the slope in units of $e^{-/s yr^{-1}}$ (top) and $\% yr^{-1}$ (bottom). In §4 we discuss possible explanations for this effect.
Fig. 4.— Mode count rates for the medium-bands as a function of MJD. Here the plot symbols are the same as in Figure 3, but here we do not apply the iterative pixel masking for persistence and scattered light.
Fig. 5.— Mode count rates for the narrow-bands as a function of MJD. Here the plot symbols are the same as in Figure 3, but here we do not apply the iterative pixel masking for persistence and scattered light.
Fig. 6.— Internal flat-field images for broad-band filters. We show the master stack (left column) and the ratio of the cycle stack to the master stack (subsequent columns) for each cycle from SMOV to cycle 21 (as indicated along the top) — the data are incomplete for cycle 22. Along the bottom we show the color bar (the top bar is for the master stacks and bottom bar is for the ratio of cycle-to-master stacks). We mark bad pixels in cyan. Although there is a modest decline in the mode count rate with time, there is no significant evidence for any pixel-to-pixel variations over time for the broad-band filters. The medium- and narrow-bands show qualitatively a similar behavior, however the stacks are considerably noisier due to lower number of frames (see Table I).
Fig. 7.— Pixel distributions for ratios of internal flats. The panels here have the same layout and brightness range as in Figure 6. The ratio images (everything but left-most column) have brightness distributions that are very nearly Gaussian with standard deviations of \( \sim 0.2\% \) (as indicated in each panel). Therefore there is little pixel-to-pixel variation of the internal flat since SMOV, consistent with the visual inspection of Figure 6.
In Figure 8 we show the slopes from Figures 3-5 as a function of wavelength (where we adopt the PHOTPLAM and PHOTBW as the central wavelength and width, respectively). Although these slopes for the medium- and narrow-band filters are not corrected for persistence effects, it is still clear that decrease in count rates are wavelength-dependent — with the bluest bands decreasing the most.

4. Discussion

We observe a weak decrease in the mode count rates and no significant pixel-to-pixel variation with time for the IR broad-band data. We consider five explanations for these behaviors:

1. **Loss in detector sensitivity:** This seems unlikely as monitoring of the zeropoints has not uncovered a decrease in sensitivity of similar amount of this timescale (Kalirai et al. 2011).

2. **Scattered light:** During SMOV, it was noticed that there can be occasional scattered light in the IR internal flats, which has been attributed to light scattering around the diffuser paddle (Baggett 2009). The WFC3 channel-select mechanism (CSM) is placed in the beam for external IR images and removed for external UVIS imaging and IR internal flat fields. As mentioned above, this is a relatively rare phenomenon and most common in the early cycles. Furthermore we specifically remove any frame which visually shows excesses, so this is unlikely to play any role in the observed trends.

3. **Changes in persistence modeling:** As the persistence model matured (Long et al. 2011, 2013), the WFC3 Team began to preemptively mitigate persistence by not scheduling deep observations shortly after observations of very bright sources (the so-called “bad actors”). We do not think this effect is relevant since we are very aggressive in removing frames with scattered light and clipping persisted pixels. Furthermore we include additional steps to remove low-level, long-term persistence effects, which are not in the standard persistence model.

4. **Order of observations:** The order of the broad-band observations for these internal flats has remained mostly constant over the cycles. With minor deviations, the order has largely been F140W, F105W, F110W, F160W, and F125W. Therefore we do not suspect any changes in the observational plan has introduced the observed signals.
Fig. 8.— The change in the mode count rate as a function of bandpass. Here the color of the plot symbol indicates the width of the bandpass, whether broad- (blue), medium- (green), or narrow- (red) band filters. As discussed in § 3, we omit the additional masking stages (steps 2-4) for the medium- and narrow-band filters due to the lack of clean data. Roughly half the bands are consistent with no change in the mode count rate, but the bluest bands $\lambda \lesssim 1.3 \mu m$ show significant decreases with time of $\sim 0.3\% \ yr^{-1}$. Therefore if it is the tungsten lamp fading as we argue in § 4, then it seems that the blue flux is decreasing making the lamp effectively redder with time.
5. **Evolution of the tungsten lamp:** This explanation seems most likely; tungsten lamps are known to dim over time as the tungsten vaporizes and darkens the interior envelope (Baggett 2008). Furthermore, the internal flats used for the UVIS bowtie monitoring show a similar decline in output ($\sim 0.5\% \, \text{yr}^{-1}$), which was slightly faster early in the mission when the lamp was heavily used (Bourque & Baggett 2013). Moreover, we expect the lamp to redden as it ages (Baggett 2008), which is qualitatively consistent with Figure 8.

If the lamp-aging hypothesis is correct, then there are a few predictions that we can make. First, the WFC3/UVIS internal flats taken with a similar tungsten lamp (in fact from the same production batch) should show a similar fading, particularly for the red bands (such as F850LP). Although the same lamp can in principle feed both detectors, this would require a modest operational change and is not currently planned. In a forthcoming ISR, we will present analysis for the UVIS detector (including both the tungsten and deuterium lamp). Second, the slight decline in brightness is qualitatively consistent with the hypothesis, but we also expect a rapid brightening shortly before the lamp dies, as tungsten filament begins to shrink and the electric current spikes. Of course this observation is a worrisome sign, indicating the lamp is very close to burning out. Therefore it is important to continue monitoring the health of the lamp, and prepare for switching to the backup bulb.

5. **Summary**

We have analyzed 1067 individual FLTs of the internal tungsten lamp that were taken over a 7 year baseline to check for variations in the detector, whether spatial or in overall intensity. For the broad-band filters, we find no evidence for significant pixel-to-pixel variations and that the mode count rates decrease at a rate of $\sim 1 \, \text{e}^- \, \text{s}^{-1} \, \text{yr}^{-1}$ (or $\sim 0.3 \% \, \text{yr}^{-1}$), which we attribute to the aging of the tungsten lamp. Furthermore the decrease in mode count rate seems to be wavelength dependent, which implies that the tungsten lamp becomes effectively redder over time. We have begun to analyze the internal flat-fields for the UVIS channel, many of which were taken through a similar (but not the exact same) tungsten lamp. While UVIS is not affected by image persistence, it does have other issues, chiefly among them are losses due to charge-transfer efficiency, which can rule out persistence as a culprit for the changes in count rates. But if similar losses are seen in the UVIS detector, then this serves to support the lamp fading hypothesis.
6. Acknowledgments

We thank L. Knox, N. Pirzkal, J. MacKenty, and H. Gunning for many helpful discussions on the nature of the instrument, persistence modeling, and various other aspects/issues discussed above.

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