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# Characterizing Persistence in the WFC3 IR Channel: Finite Trapping Times

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**ABSTRACT**

*The WFC3 IR array on HST, like other IR detectors, shows afterglows, known as persistence, arising from earlier exposures to bright sources. Here we report on calibrations using the internal lamp of the IR channel, intended to characterize one aspect of persistence, namely changes in the amount of persistence as a function of the time pixels are held at or near saturation. We find that persistence increases in amplitude and duration as this time increases. The effect is sufficiently large that it should be incorporated into estimates of the amount of persistence that is expected in the IR detector of WFC3.*

## Introduction

Persistence is a property of the IR detector that is part of the WFC3 IR channel. Afterimages from earlier exposures are sometimes observed when portions of the detector have been exposed to fluence levels that approach saturation in the detector. These afterimages can lead to spurious scientific results if not considered in the analysis of WFC3/IR data.

Considerable effort has gone into characterizing persistence in the WFC3/IR channel. This effort has resulted in the development of a functional model that allows observers to locate regions of their images that should be excluded from analysis and in some cases to subtract persistence from their images (Long et al. 2012). The initial model predicts persistence from an earlier exposure based on the total number of electrons generated in the earlier exposure (hereafter the fluence) and the time since the exposure. The current model predicts the same amount of persistence from a 10 s exposure of a source with a count rate of 10,000 e $s^{-1}$ as one from a 100 s exposure of a source with a rate of 1,000 e $s^{-1}$. It does not take into the account the possibility that persistence depends upon the entire history of the exposure.

Persistence in IR detectors is due to imperfections in the diodes that comprise the active pixels of IR arrays (see Smith et al. 2008ab for details). Free charge is trapped by these imperfections as voltage levels within the diode change during the course of the observation of bright sources. Afterimages are created as this charge is released during subsequent exposures. If the timescale to trap charge is comparable to or greater than the exposure time, one expects persistence to vary with the initial exposure time, and that is observed in other IR detectors.

Here we describe a series of internal calibrations designed to provide information about how persistence varies in the WFC3 IR array depending upon how long a pixel is held at a certain fluence level. We concentrate on the basic results of this calibration program; an attempt to create a more complete model of persistence in WFC3 will be described elsewhere.

## Observations

Each visit in this calibration program (Prog. ID. 13086) consisted of a dark exposure, a Tungsten lamp exposure, and a series of dark exposures. The initial dark exposure was used simply to verify that the IR detector was in a "normal state" at the start of the visit. The Tungsten lamp exposure consisted of a single MULTIACCUM sequence using the F140W filter. This Tungsten lamp with this filter produces an average photo-electron rate of 1630 e $s^{-1}$ $pix^{-1}$ on the WFC3 IR array. Unlike a normal Tungsten lamp exposure, special commanding (LAMPDUR) was used to turn off the lamp in the middle of the exposure. Since the IR array is not reset until the end of the MULTIACCUM sequence, this results in pixels within the array being held (approximately) at fixed fluence from the time the lamp is turned off. By varying the length of the MULTIACCUM, the hold time was varied from very nearly 0 to about 800 seconds. The persistence was then measured using a series of darks following immediately after the Tungsten lamp exposure.

The observing program consisted of 36 visits. Persistence was measured at 6 different fluence levels and 6 different delay times. Our intent was to space the levels from 40,000 e to 140,000 e in 20,000 e increments. However, the actual levels measured in the raw data files were less than we expected at 40,000 and 60,000 e, the two sets of measurements where the Tungsten lamp exposures were not significantly affected by saturation. In the Tungsten lamp exposures intended to produce 40,000 e, we measured 28,000 e, or 12,000 e less than expected. In the exposures intended to produce 60,000 e, we measured 47,000 e, or 13,000 e less than expected. The reason was not due to a low photo-electron rate from the Tungsten lamp and the F14OW filter. Rather, in planning the observations we did not appreciate that time zero for the LAMPDUR command occurred at the point where the flight software initiated the MULTIACCUM exposure sequence rather the time of zero read. We should have added this overhead

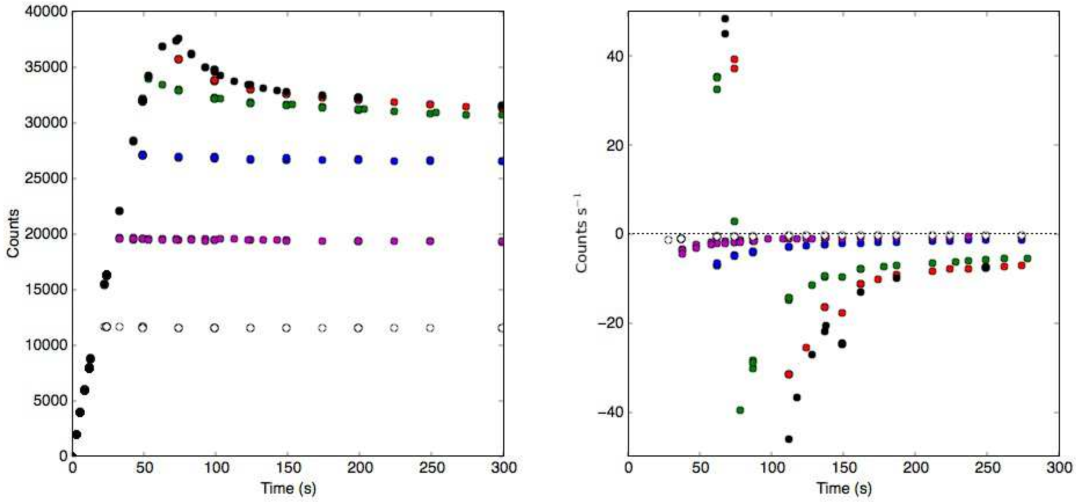


**Figure 1.** Characteristics of the Tungsten flats. The left panel shows the average value of each read in the "raw" data file (after subtraction of the zero-read as a function of time from the beginning of the exposure. All of the data points for Tungsten flats intended to reach the same fluence level are shown in the same color. The rise in counts stops when the Tungsten lamp is turned off. Note that raw counts for fluence levels of 107,000 and 127,000 e are almost identical, because at this point, the detector is fully saturated. The right panel shows the count rate measured as the change in DN per unit time. The rates which are positive reflect times when the lamp was just being turned off between two reads and can be ignored. Except for these, the other data points should all be 0 if the charge were held perfectly. All of the values are negative indicating that charge is being lost. Larger fluence levels, particularly those above 67,000 e, show greater losses.

time to our LAMPDUR commands. This overhead should have included a setup time of about 8 seconds (See the Appendix for details). Given this, and a rate of 1630 e $s^{-1}$ $pix^{-1}$, all of our the fluence levels should have been low by about 13,000 electrons, close to the values observed in the raw data files. In the analysis which follows, we have revised the fluence levels to use the measured values of 28,000 e and 47,000 e for our shortest LAMPDUR setting of 25 and 37 seconds, and subtracting 13,000 e for the settings where the exposure was long enough that the detector was saturated before the Tungsten lamp was turned off. Based on this, our mean Tungsten Lamp exposure levels were approximately 28,000 e, 47,000 e; 67,000 e; 87,000 e; 107,000 e, and 127,000 e.

The initial darks were all nominal; all of the visits were used in the analysis that follows.

The raw pixel values for each Tungsten lamp exposure as a function of time within the exposure are shown in left panel of Figure 1. The values plotted are the average of the raw pixel values in the active region of the detector after the zero-read had been subtracted. All 36 visits are plotted; visits with the same fluence are plotted in the same color. For example, all of the visits in which the desired fluence level was 67,000 e are plotted in blue. The figure shows that the Tungsten lamp rates are quite uniform during the time period when the lamp is turned on. At each fluence level, the measured raw pixel values are quite repeatable during the period after the lamp has been turned off.

The figure also shows the effects of saturation. The curves for 107,000 e (red) and 127,000 e (black) are almost identical, and the difference in the curve for 87,000 e (green) and 107,000 e is smaller than that between, for example, 28,000 e (white), and 47,000 e (magenta). Furthermore, at high fluence levels, 87,000 e and above, there is a noticeable decline in the measured value after the lamp has been turned off. The array is not able to "hold" charge above saturation (which is nominally 70,000 e).

A plot of the count rate measured in data numbers per second is shown in the righthand panel of Figure 1. It shows that the measured count rates are actually negative at all fluence levels (after the Tungsten lamp has been turned off), but confirms that the effect is largest at the higher fluence levels. Inspection of the data obtained during the Tungsten lamp exposures shows that the effect is largely independent of amplifier or position on the detector. For Visit 56, in which the nominal fluence was 127,000 e, the raw count values decline about 11% from the first image extension read out after the lamp was turned off until the last about 800 seconds later. Inspection of the images revealed a slight gradient across the detector, a decline of about 10% in the lower right quadrant compared to 11% in the upper left quadrant.

In order to determine the amount of persistence induced by the Tungsten lamp exposures, we reprocessed the data using version 3.1.2 of the WFC3 calibration pipeline (CALWF3). Prior to reprocessing, we edited the header keywords of the raw data files so that the processing steps were those for a standard science observation. We used a dummy pixel flat ("pflat") with all data values set to 1. As result of this calibration procedure, the "ima" and "flt" files record the flux in units of e $s^{-1}$. We carried out the analysis that follows on the "ima" files since these provide the highest time resolution. The values of an extension in an "ima" file represent the flux between the 0th read and the time associated with the extension. The flux $r_{i,i-1}$ between two reads is therefore:

$$r_{i,i-1} = \frac{(r_i t_i - r_{i-1} t_{i-1})}{(t_i - t_{i-1})} \tag{1}$$

where $r_i$ and $t_i$ are the rate recorded and time of the $i^{th}$ read.

Plots of the median value of the rates from two visits in which the Tungsten lamp exposure had a fluence of 67,000 e are shown in Figure 2. In calculating the rates, only "good" pixels, defined as pixels with data quality of 0 in the "dq" extension of the "ima" readout, have been included. The two curves show the persistence resulting when the MULTIACCUM exposure ended when the Tungsten lamp was turned off and when the MULTIACCUM exposure extended 750 s after the Tungsten lamp was turned off. In both cases, persistence decays roughly as a power law function of time. However, the magnitude of the persistence is greater and the power slope of the decay is flatter for the data set in which the fluence was held for at 67,000 e for a long period of time.

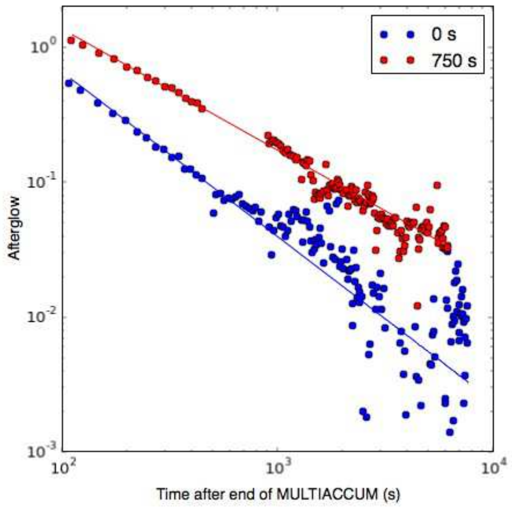


**Figure 2.** Examples of the persistence following a Tungsten lamp exposure. Both data sets were obtained in a Tungsten lamp exposure with a fluence of 67,000 e. The blue data points were obtained in a visit in which the Tungsten lamp was turned off at the same time as the MULTIACCUM sequence ended, while the red data points came from a visit in which the MULTIACCUM exposure extended for 750 s after the Tungsten lamp was turned off. Power law fits to the data are also shown.

Figure 2 shows a number of other characteristics of the measurements. Despite the fact that almost $10^6$ pixels are being averaged, there is a lot of scatter in the measured rates. This scatter reflects intrinsic limitations in measurements of this type because the entire array is illuminated by the Tungsten lamp, and we are unable to separate changes in persistence from changes in the dark current. The scatter is often worse in the first few reads of a MULTIACCUM image, in part because the time interval involved is smaller than in later reads, and in part because there appear to be some transient effects associated with the first few reads in every MULTIACCUM image.

## Analysis

In order to quantify differences in the persistence as a function of fluence and hold times, we have fit the median fluxes obtained from the "ima" files to a power law of the form

$$R(t) = A\left(\frac{t}{1000s}\right)^{-\gamma}, \tag{2}$$

where t is the time from the end of the Tungsten lamp MULTIACCUM exposure.

In carrying out the fits, we minimized the function

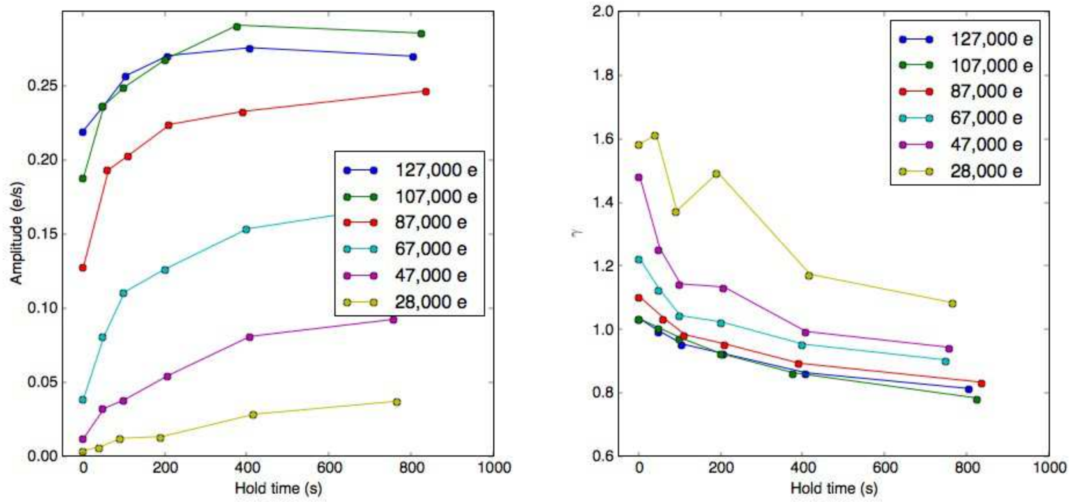


**Figure 3.** Fitted amplitude of persistence at 1000 s (left) and power law index ($\gamma$) as function of hold time.

$$\chi^2 = \sum \left( \frac{r_{i,i-1} - \int_{t_{i-1}}^{t_i} R(t)dt}{t_i - t_{i-1}} \right)^2 , \tag{3}$$

which has the effect of de-weighting the first few reads in each dark exposure.

The fitted amplitudes A and slopes $\gamma$ are shown in Figure 3 as a function of hold time. As expected, the amplitude generally increases with fluence and with hold time. In the context of a trapping model, this indicates that traps are not filling instantaneously. In terms of percentage, the increase is greatest for smaller fluences. It is also clear that the amplitudes are not growing linearly with time (except perhaps at a fluence level of 28,000 e); this suggests that in 1000 seconds, either most traps have been filled or at least that the number of traps per unit trapping time decreases significantly for times longer than 1000 s.

The measured slopes at low fluence levels, as shown in the right panel of Figure 3, are steeper than at higher fluence levels, and the slope decreases as hold time increases. In the context of a trapping model, the tendency toward flatter slopes as hold time increases suggests that the traps with long trapping times have longer release times. Steeper slopes at low fluence rates are more ambiguous to interpret. This characteristic could either be due to the fact that trap density increases at fluences near saturation and so some traps are exposed to free electrons from very short times, or it could be that traps exposed at lower fluence levels actually have shorter release times. Either would produce the observed behavior.

In commenting on Figure 3, we have largely ignored the data for fluence levels of 107,000 e and 127,000 e. The fact that the amplitude and slopes at these fluence levels are very similar is surely a saturation effect. As we noted earlier, although the Tungsten lamp was held on longer to reach a nominal fluence level of 127,000 e than it was for 107,000 e, the raw data values recorded in the images were very similar.

A careful inspection of the left panel of Figure 3 shows instances where the persistence resulting from a Tungsten lamp exposure designed to reach 107,000 e is higher than the curve for a fluence level of 127,000 e. We believe this is most likely due to the lack of repeatability in experiments of this type. Ideally, we would have carried out multiple versions of the same experiment to determine the repeatability directly.

The variations we see are unlikely to be due to the lamp itself, as the lamp flux from July 2009 to September 2012 has been shown to be stable to about 0.4% rms (Dahlen, ISR 2013-04). The lamp is turned on during the time that the chip is being scrubbed and allowed to equilibrate before the Tungsten lamp exposure takes place. We are using special commanding to turn off the lamp, which is not the case in a standard observation with the lamp, but the fact that the results for the Tungsten lamp images (see Figure 1) show no indication of variation at the lower fluence levels suggests that this is not a problem.

We know from previous experience that measurements of persistence after Tungsten lamp exposures are not completely repeatable. Part of this is due to variations in the dark current, which cannot be removed in the current experiments. The mean dark current for the WFC3/IR detector is 0.046 e $s^{-1}$, and according to Hilbert & Petro (2012), ramp-to-ramp variations, rather than long-term trends dominate dark current fluctuations. The variations are 20% to 30% of the mean rate, or of order of 0.01 e $s^{-1}$, while the amplitude difference we measure with our power law fits for fluences of 107,000 and 127,000 e is about 0.02 e $s^{-1}$. We know from experience that measurements of persistence using stars (which allow the subtraction of a local background) tend to be more consistent than measurements using the Tungsten lamp as a stimulus (but observations with stars interfere more with HST's science program). However, even these experiments show some variation in persistence from observation to observation.

Despite questions about repeatability however, the basic results are clear. Persistence in the IR detector on WFC3 IR is affected by the amount of time pixels are held at high fluence levels.

## Discussion and Conclusions

The model of persistence developed by Smith (2008ab) assumes that there are imperfections in the depletion region of a detector diode that can trap free charge. The traps are exposed to free charge when photoelectrons released by exposure to light partially discharge these reverse-biased diodes. There is more persistence for bright sources because a larger region of the depletion region is exposed. In the case of the IR detector on WFC3, the density of dislocations increases greatly near saturation (Long et al. 2012). If all dislocations had similar release times, then one would expect persistence to decay exponentially. Since it does not, there needs to be a wide range of release times. Our

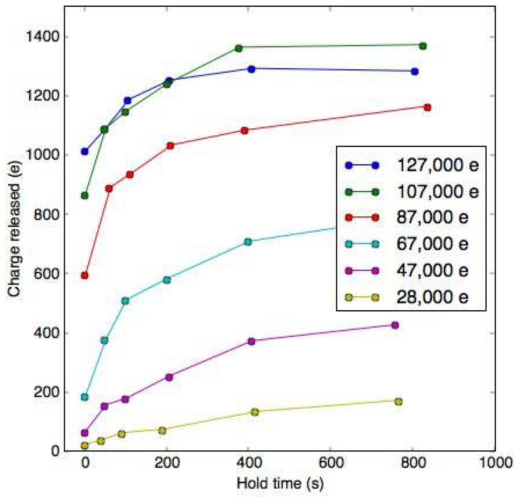


**Figure 4.** Effective number of electrons released between 100 and 10,000 s as a function of the time delay.

initial model for persistence in the WFC3 detector took all of these effects into account.

We have measured significant changes in the amount of persistence seen after Tungsten lamp exposures that depend on how long a pixel was held at a specific fluence level. Longer hold times lead to higher persistence amplitudes and flatten the slope of power law decays in persistence. The experiment we have carried out here, which uses special commanding to maintain a fixed fluence level on the detector for a long period of time, is not identical to a science observation. However, the MULTIACCUM sequences used for science observations range in duration from a few seconds to nearly 3,000 s. A large fraction of these exposures saturate some portions of the image, and this implies that depending on the exposure length, these saturated pixels have been near saturation for differing amounts of time, depending on what MULTIACCUM sequence was chosen.

The fact that the amplitude of persistence, the length of time persistence lasts, and the effective numbers of traps all increase with hold time implies that trap and release times are comparable to exposure times on WFC3, and explains in part why tuning the parameters (specifically A and $\gamma$) in our current model provides more accurate persistence-subtraction than a single set of parameters. The effects of finite trapping times are large enough that they ought to be incorporated into a new model for persistence in WFC3. An attempt to develop such a model will be discussed elsewhere.

Finally, we note that the power law function that we have used to describe persistence in the WFC3 IR detector cannot apply over all time scales. The integral of the current over time would be unbounded both at short times and, for slopes less than 1, at large times. However, we can integrate the power law over a characteristic interval of 100 s to 10,000 s to estimate the total effective number of traps that affect persistence when it is measurable in our observations. This is shown in Figure 4. For a fluence of 87,000 e, the effective charge released as persistence is about 1100 e, or about 1.3% of the fluence. This is the worst case, and is consistent with idea (see, e. g. Long et al. 2012) that the trap density increases with fluence until the detector is saturated.

## *Acknowledgements*

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## Appendix – The Detailed Explanation for the Observed Fluence Levls

The LAMPDUR command was implemented as a delay between the time in the SMS for the beginning of IMULSEQ command and a ILAMPWR, POWER(OFF) command. Both of these commands take time to execute and the difference in times should have been taken into account in estimating the amount of fluence expected in the Tungsten lamp exposures. The fact that the fluences were less than expected is due to the fact that IMULSEQ requires more time to reach the zero-read stage in the MULTACCUM command than the Tungsten lamp turnoff command does to power off the lamp.

Based on an analysis of the timing of commands from WFC3 provided by Tom Wheeler, there is a delay of 10.6 seconds between the time a IMULSEQ command, which executes MULTIACCUM sequence, appears in an SMS and the end of the zero read for a full frame exposure. The time includes the time to transfer the command from the NSSC-1 to WFC3, the time to process the exposure command, the time to calibrate the ADC, the time to flush the detector, and the time to carry out the zero-read portion of the MULTIACCUM sequence.

The time taken to turn off the lamp is not as accurately known, although it should be quite repeatable. The command takes a total of about 3.4 seconds to complete, including the 1.4 s time to transfer the macro command from the NSSC-1 to WFC3, but where exactly within the macro command, power to the lamp is turned off would require considerably more study. The delay could be anywhere from 1.4 to 3.4 seconds.

Therefore, the difference in exposure time could have been anywhere from 7.2 to 9.2 seconds from the time we had expected when we planned the observations . At a rate of 1630 e/s, this corresponds to 11,700 to 15,000 e. The fluences we observed were deficient by 12,000 to 13,000 e, toward the minimum of this range.