WFC3/IR Channel Behavior: Dark Current, Bad Pixels, and Count Non-Linearity

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Abstract.
Using data taken during Servicing Mission Observatory Verification (SMOV) and Cycle 17, we have characterized many aspects of the on-orbit behavior of the IR Channel. We find the mean dark current in the IR channel to be $0.042 \text{ e}^-/\text{s/pixel}$. We have also recently finished the creation of a bad pixel mask for the IR detector, which contains a list of pixels with non-nominal behavior that should be ignored in WFC3/IR data analyses. An update to the non-linearity correction file will be produced soon. Analysis of cycle 17 non-linearity calibration data is on-going.

1. Introduction

With the installation of WFC3 into HST during Servicing Mission 4 in May 2009, the primary task of the WFC3 team has been to ensure a high quality calibration of the data produced by the instrument. We present here some basic results of the behavior of the IR channel. This includes dark current and signal non-linearity behavior, as well as a description of the updated bad pixel mask. Full details of each of these behaviors can be found in the referenced Instrument Science Reports (ISRs). We summarize here the important highlights of each investigation.

2. Dark Current

Unlike the dark current behavior observed in CCD-derived data, the timing pattern used to collect data with the WFC3/IR detector has a large impact on the dark current accumulation rate. Analyses of ground testing data have shown that dark current signal does not increase linearly with time, but instead is initially zero (or even negative) followed by a regime where the signal does increase linearly with time. (Hilbert and McCullough, 2009) Figure 1 shows the mean dark current versus time for several sample sequences as measured in Cycle 17, where this pattern in apparent. These observations are very similar to those obtained during ground testing.

Given this behavior, dark current in WFC3/IR data must be subtracted from science data on a read-by-read basis, using a dark current file produced using the same sample sequence as the science data. Calculating an image of the mean dark rate and scaling that image by the exposure time of each read would result in an over- or under-subtraction of the dark current signal, as implied by the non-linear dark signal in Figure 1. Figure 2 is a diagram showing this dark current removal strategy.

In preparation for dark current characterization and calibration, we have collected a large quantity of WFC3/IR dark current data during (Servicing Mission Observatory Verification) SMOV and Cycle 17. Ramps were acquired at all supported full-frame and subarray sizes for all sample sequences. For each array size/sample sequence combination, we calculated a pixel-by-pixel sigma-clipped mean dark current ramp. These ramps have all either been delivered to the calibration database (in the case of the full-frame ramps, on
Figure 1: Mean dark current signal versus time for three different sample sequences. Note that dark current behavior in the early reads of a ramp depends on the sample sequence used to collect the data.

Figure 2: Diagram showing the dark current subtraction strategy for the WFC3/IR channel.

April 8, 2010, or will be delivered shortly (subarray observations). These updated dark current reference files represent a significant (4-8X) increase in signal to noise ratio over the previous dark current files in the calibration pipeline. Each new dark current reference file is a mean ramp created from 16 to 63 individual ramps, depending on sample sequence. The old dark current ramps were each the mean of only 3 ground-based dark current ramps.
For any observers with science goals where an accurate removal of dark current is critical, we recommend reprocessing your data with these new dark current files.

To give a general idea of the dark current behavior, we provide some basic statistics on the highest signal to noise mean dark current ramp below. Figure 4 shows a histogram and the cumulative distribution of dark current rates for all pixels. The peak dark current rate is 0.042 e-/sec. Only 0.7% of the pixels have a dark current rate above the hot pixel limit of 0.40 e-/sec. Figure 3 shows an image of the final read of the highest signal-to-noise dark current ramp, in order to give an idea of the relative dark current levels across the detector. We have also monitored the hot pixel population during SMOV and Cycle 17 and found it to be stable. We see no increase in the total number of hot pixels since the beginning of SMOV. The hot pixel population is also unchanged after monthly UVIS channel anneals, during which the IR detector temperature increases by 35°C.

![Figure 3: Image showing the final read of a high signal-to-noise dark current ramp. Histogram equalization stretch from 0 to 0.4 e⁻/second.](image)

3. Bad Pixel Table

During the various ground testing campaigns for the WFC3 IR channel, efforts were made to identify and flag any pixels on the detector which were bad in ways that made them scientifically useless. (Hilbert et al., 2003 and Hilbert, 2007) With WFC3 successfully installed in HST, we wished to update this list of bad pixels to reflect any changes since ground testing. During SMOV and the early stages of Cycle 17 a large amount of calibration data were obtained, allowing for an on-orbit bad pixel search. This was accomplished using a combination of dark current and internal flat field observations. Results of this bad pixel table update are detailed in Hilbert and Bushouse (2010).

Using the flat field and dark current observations, we searched for three types of bad pixels. These included: “dead”, “unstable”, and “bad in the zeroth read”. Our goal was to produce a table that lists pixels which are permanently bad. For example, a dead pixel, which exhibits little or no sensitivity to illumination, will likely always remain in that state. By focusing on permanently bad pixels, our aim is to have a table that changes little over time and can be applied to any WFC3/IR observation. Pixels which are bad in potentially
more transitory ways, such as those with higher than average dark current, are flagged in other types of reference files, such as dark current reference files. The populations of bad pixels mentioned below were all combined into a single table which was uploaded into the calibration database on April 12, 2010. This new table replaced that produced from ground testing data, and should be used for the identification of bad pixels in all on-orbit data. Table 1 shows the flag values associated with each type of bad pixel. Final values in the bad pixel table are calculated using bit-wise addition. For example, a pixel found to be both bad in the zeroth read (8) and unstable (32), then that pixel will have a value of 40 in the final bad pixel table.

Figure 5 shows an image of the new bad pixel table, where all pixels flagged as bad in any of the ways described below appear white.

<table>
<thead>
<tr>
<th>Flag Value</th>
<th>Bad Pixel Type</th>
<th>Pixels Affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Dead</td>
<td>3,910</td>
</tr>
<tr>
<td>8</td>
<td>Bad Zeroth Read</td>
<td>4,990</td>
</tr>
<tr>
<td>32</td>
<td>Unstable</td>
<td>10,885</td>
</tr>
<tr>
<td>512</td>
<td>Affected by Blob</td>
<td>4,534</td>
</tr>
</tbody>
</table>

Table 1: Bad pixel flag values and descriptions, along with the number of science pixels flagged as each type in the new bad pixel table.

### 3.1. Bad Zeroth Read Pixels

Bad zeroth read pixels exhibit anomalous signal in the zeroth read of a data ramp (the read immediately following the detector reset at the beginning of an IR exposure sequence), usually due to being shorted or unbonded (Hilbert et al., 2003). We used the zeroth reads
of raw (uncalibrated) dark current ramps for this search. We first created a sigma-clipped mean zeroth read image. We then created a histogram of the values in this mean zeroth read for each quadrant of the detector. A Gaussian was fit to each histogram, and pixels falling more than $3\sigma$ from the mean value were flagged as bad. In order to catch any pixels which may have been inconsistent from ramp-to-ramp, we also repeated the above process on each input ramp individually. Any pixels which were more than $3\sigma$ from the mean in some ramps but not others were caught with this additional step. With this two-step method, we identified 4,990 pixels (0.5% of the detector’s light-sensitive pixels) which are bad in the zeroth read. Figure 6 shows an example of a histogram and gaussian fit. Pixels identified as bad in the zeroth read were given a value of 8 in the bad pixel table.

3.2. Dead Pixels

These are pixels with very low quantum efficiency and measure little or no signal when illuminated. As with the bad zeroth read pixels, we used a two step process to find dead pixels. First, we created a mean flat field image, using the final read from each ramp in a large set of flat field files. Any pixels exhibiting zero or negative signal in the mean flat field were flagged as dead. Next, we looked for pixels with very low, but not necessarily zero, quantum efficiency. For this, we moved pixel-by-pixel across the detector. For each pixel, we calculated the sigma-clipped mean value in the surrounding 50 by 50 pixel box. If the pixel had a signal less than 30% of the local mean signal, we flagged it as dead. By using this strategy, we hoped to compensate for the non-uniformity of the flat field illumination level. By comparing the signal from a pixel to that of its neighbors, we avoided marking a pixel as bad simply because it was located on a portion of the detector with a lower illumination level compared to other areas. Finally, we manually marked the pixels comprising the “death star” as dead. This feature (seen as the largest circular feature along the bottom edge of Figure 5) is a collection of poorly performing pixels resulting from a manufacturing defect. Combing the results from these three searches, we found 3,910 dead pixels (0.4% of the detector’s light-sensitive pixels), which were marked with a 4 in the bad pixel table.
3.3. Unstable Pixels

Unstable pixels were first observed on the WFC3/IR detector during ground testing. Pixels within this population display variable or unrepeatable signal measurements across a set of nominally identical ramps. The physical reason behind this behavior is unknown. A basic census of unstable pixels was taken using flat field ramps during ground testing. With WFC3 on orbit, the unstable pixel search was repeated using a larger dataset and a more thorough search.

Unstable pixels display a wide range of behaviors. Some unstable pixels appear stable and repeatable in almost all of a data set, but will then measure appreciably different signal values in just one or two ramps. Other unstable pixels display signal values that vary wildly from ramp to ramp in all observations of a data set. Figures 7 and 8 respectively, show examples of these two types of unstable pixels. Further examples can be found in the appendix of Hilbert and Bushouse (2010). Investigations across a wide range of IR data as part of this study also revealed some pixels which were unstable in a set of dark current ramps but stable in a set of flat field ramps, and others with the opposite behavior.

Due to the complexities of this behavior, we used multiple search methods and datasets to identify unstable pixels. By performing the search on a set of flat field ramps, and then repeating the search on a set of dark current ramps, we hoped to arrive at an accurate map of unstable pixels across the IR detector.

The first search method involved comparing the measured signal rate in a mean flat field image versus those in each of the individual flat field images in a dataset for a given pixel. If a pixel showed a signal rate in any individual image that was more than $N-\sigma$ from the mean value, the pixel was marked as unstable. Figure 7 shows an example of an unstable pixel found with this search method. For our final unstable pixel search, we settled on a value of 5 for $N$. Using this limit, we identified 2,223 unstable pixels using the flat field dataset, and 6,001 unstable pixels using the dark current dataset. Since this
method relies on the uncertainty value in the mean flat field, it worked best at identifying pixels which were largely repeatable from ramp to ramp, but displayed anomalous signal in a small number of ramps.

The second search method was designed to identify unstable pixels which had much more variable signal rates from ramp to ramp. These pixels produced large uncertainty values in the mean flat field and therefore were potentially able to slip through the N-σ search. In this case, we searched for pixels with a measured signal rate that varied by more than a certain percentage of the mean measured rate. Figure 8 shows an example of a pixel falling into this category. Details of the calculation can be found in Hilbert, 2010. After some trial and error, we set our threshold to be a 0.93% variation relative to the mean signal rate for the flat field dataset, and a 61.5% variation for the dark current data. Using these values, we found 3,795 unstable pixels in the flat field data, and 3,318 in the dark current ramps.

Combining the populations of unstable pixels from these various searches, we find a total of 10,885 unstable pixels (1.06% of all science pixels) on the IR detector. These pixels are flagged with a value of 32 in the bad pixel table.

3.4. Blobs

The final type of bad pixel added to the bad pixel mask was pixels which were affected by blobs. WFC3 ISR 2010-06 (Pirzkal, Viana & Rajan 2010) provides details on these blobs. Essentially, these blobs are collections of pixels with decreased throughput relative to other pixels. This is most likely due to particulates resting on the Channel Select Mechanism (CSM). For the purposes of the bad pixel table, we took a list of blob positions and diameters, provided by Pirzkal, and mark the blob-affected pixels with the value of 512 in the bad pixel table. In all, 4,534 pixels (0.44% of all science pixels) are flagged as affected by blobs.
4. Non-Linearity Behavior

The measured signal level from HgCdTe detectors, such as that in the WFC3/IR channel, is a non-linear function of the number of incident photons. Unlike that in CCDs, this non-linearity effect is significant down to signal levels which are a relatively low fraction of the full well.

Using flat field ramps as well as observations of external targets, we have devised a non-linearity correction algorithm for IR channel data. The correction currently in place was derived using flat field data from ground testing. On-going analysis using on-orbit flat field ramps as well as observations of 47Tuc will produce an updated correction to be put in place shortly. Here we describe the basic method used to calculate the non-linearity correction. Further details on this method can be found in Hilbert (2008).

In order to calculate the magnitude of the non-linearity at various signal levels, we began by creating a mean flat field ramp. Figure 9 shows a plot of the measured signal versus time for one pixel of this mean flat field in the series of connected black diamonds. The red line shows a best-fit line created using only reads with less than 4,500 DN, and then extended out to the remaining reads. Note that the measured signal appears linear at low signal levels, but begins deviating from this line at a signal level well below the marked saturation level. We define the signal level at which the measured signal is below the best-fit signal by 5% as the saturation level for that pixel. Our goal is to remove the non-linearity effects for signals below this saturation level.

By taking the difference between the best-fit line and the measured signal in each read, and dividing the difference by the calculated best-fit signal, we are able to calculate the percentage of the measured signals’ non-linearity at each signal. The black diamonds in Figure 10 show this calculated non-linearity versus signal level. The red curve in Figure 10 shows the best-fit 3rd order polynomial to the black diamonds. The best-fit coefficients of this red curve can be used to remove non-linearity effects from all measured signals in this pixel using Equation 1.
Figure 9: Linear fit to the initial reads ($\leq 4500$ DN) of a flat field ramp, for one pixel.

Figure 10: Polynomial fit to the measured non-linearity in a flat field ramp, for one pixel.

\begin{equation}
    s_{\text{corr}} = s_{\text{meas}} \times (1 + A + B \times s_{\text{meas}} + C \times s_{\text{meas}}^2 + D \times s_{\text{meas}}^3)
\end{equation}

In this equation, $A$ through $D$ are the best-fit polynomial coefficients, while $s_{\text{meas}}$ is the measured signal, and $s_{\text{corr}}$ is the corrected signal, with non-linearity effects removed. During the calculation of these coefficients when using the ground testing data, the limited amount of
data implied large uncertainties in the best-fit polynomial coefficients. We therefore decided to calculate the mean coefficients across each quadrant of the detector, and use these when correcting signals for all pixels in each quadrant. The blue line in Figure 10 shows the curve produced by the mean quadrant 2 coefficients. In this case, the difference between the best-fit polynomial for the individual pixel and that for the quadrant mean is small. For other pixels, this difference is more significant. Part of our on-going analysis using the on-orbit flat field data is an investigation into whether the pixel-by-pixel or quadrant-averaged correction provides a better non-linearity correction. We are also investigating whether the non-linearity behavior is independent of the source of illumination, by comparing results obtained from flat field data to those from observations of point sources. A forthcoming ISR will detail those results.

5. Conclusions

Data from cycle 17 have been used to evaluate the behavior of the WFC3/IR channel, and produce appropriate calibration files. Calibration files derived from on-orbit data represent a significant improvement over the previous versions of these files, which were derived from ground tests. New dark current subtraction files and a new bad pixel table were uploaded to the calibration database system in early April of 2010. Any data retrieved from the archive after this time will have had these new files applied. If an accurate dark current subtraction or bad pixel flagging is important to your science goals, we recommend re-retrieving your data from the archive.

We will continue to collect dark ramps for all sample sequences in Cycle 18 and will provide periodic updates to the dark current reference files. Similarly, the bad pixel population will continue to be monitored during Cycle 18, and any necessary changes to the bad pixel table will be made.

The non-linearity correction reference file will be updated soon, based upon results from the on-going analysis.

6. Observation Planning and Data Reduction Tips

In order to mitigate the effects of bad pixels (as well as other effects), we strongly recommend that observers dither their observations. By making multiple observations of a field while moving targets around on the detector, observers will decrease the chance of having all observations of an individual target contaminated by a bad pixel. Dithered individual observations can then be combined by software such as Multidrizzle (Fruchter et al. 2009), where observations affected by bad pixels are ignored, resulting in a combined image where effects of bad pixels are minimized.

The current version of the cosmic ray rejection table (u6a1748rt_crr.fits) causes calwf3 to calculate a signal rate for all pixels on the detector, regardless of whether they are flagged as bad or not. Due to this behavior, it is important that observers consider their science goals, decide which bad pixel types are not acceptable to use in their analyses, and mask the appropriate pixels.

References

Hilbert, B., 2010, WFC3 Instrument Science Report, WFC3-ISR-2010-13 (Baltimore:STScI)