Abstract

The Advanced Camera for Surveys (ACS) Wide Field Channel (WFC) takes about 100 seconds to read out all of the pixel data from the two CCDs. During this time, dark current continues to contribute to the image noise. We call this contribution "readout dark". Readout dark increases across the detector; pixels furthest from the amplifiers (last to be read out) are subject to the most readout dark. This additional source of noise is relatively small but has yet to be quantified in detail. We find readout dark has increased over the lifetime of ACS as radiation damage has produced more warm and hot pixels (above average sources of dark current). In recent ACS/WFC full-chip images, readout dark contributes about 0.5 electrons of noise to pixels furthest from the readout amplifiers. That is, we measure read noise to be ~4.0 electrons closest to the amplifiers and ~4.5 electrons (including readout dark) furthest from them (varying somewhat for each amplifier) in recent images. This detailed understanding of the ACS/WFC readout dark should improve algorithms for bad-pixel masking and for pixel-based correction of CTE/CTI (charge transfer inefficiency), which is also most significant for pixels furthest from the amplifiers.
1. Introduction

Twelve years of cumulative radiation damage to the CCDs of the Advanced Camera for Surveys (ACS) Wide Field Channel (WFC) has resulted in two primary performance impacts: 1) During CCD readout, the charge transfer efficiency (CTE) between pixels has steadily declined over time (ACS ISR 2012-03). 2) The number of individually damaged pixels has steadily increased over time (ACS IHB Figure 4.5). These "warm" or "hot" damaged pixels have significantly more dark current than other pixels. Monthly anneals (heating the detector) have somewhat mitigated this damage, effectively "curing" some pixels. But the rate of damage has outpaced the restorative powers of the anneals (ACS ISR 2002-09).

Readout of full-frame ACS/WFC pixel data takes about 100 seconds. During that time, hot pixels leak charge along columns of the image data, as seen in the bias frame (with zero exposure time) in Figure 1. As charge packets are transferred between rows toward the serial register, hot pixels contaminate each in turn with as much as several electrons of leaked charge. These contaminated pixels are later flagged as "bad columns" to be discarded by the ACS image processing pipeline CALACS.¹

However these data need not be discarded if the readout dark profile is stable. Instead, the excess noise due to "bad columns" should simply propagate to the error (ERR) array. The excess charge is already properly subtracted from science images along with the superbias image (combination of multiple bias images, as shown in Figure 2) during image processing (ACS ISR 2004-07).

Bias frames obtained for image calibration² should be properly treated as two components: 1) a 2D bias pedestal, and 2) dark current accumulated during readout, or "readout dark", which increases with distance from the readout amplifier. This proper treatment will allow us to preserve data in bad columns (as discussed above) and should also improve CTE corrections. CTE is aided by a background or base level of charge, which fills some of the charge-traps responsible for imperfect CTE. By 2014, readout dark contributes up to several electrons per pixel, which is non-negligible for CTE improvement.

In this report, we quantify the additional charge (§2) and additional noise (§3) putatively due to readout dark over the lifetime of ACS, showing the two are consistent. We then show the

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¹ CALACS assigns bad columns flag = 128 in the data quality (DQ) array. See ACS DHB Section 3.3 Table 3.4 and http://www.stsci.edu/hst/acs/analysis/reference_files/data_quality_flags.html.
² Bias frames are obtained as part of the ACS CCD Daily Monitoring calibration programs: CAL 9647, 9673, 9674, 9675, 10042, 10059, 10060, 10061, 10367, 10389, 10729, 10758, 11041, 11042, 11043, 11879, 11995, 11996, 12384, 12397, 12427, 12729, 12792, 12783, 13152, 13153, 13154, 13589, 13590, 13591 (PIs Riess, Siriani, Golimowski) http://www.stsci.edu/hst/acs/analysis/calib_plan
observed pixel noise is accurately predicted by simulated CCD readout using the readout dark current as measured in superdarks over the lifetime of ACS (§4). Finally, we briefly discuss future implementation (§5).

**Figure 1**: One quadrant of the raw bias (zero exposure time) image `jcfuf5wlq_raw.fits` obtained Jan. 31, 2014 by the ACS CCD Daily Monitoring program (GO 13589; PI Golimowski). The bottom row is first to be read out by WFC2 amplifier C. Subsequent rows read out over the next 100 seconds exhibit additional noise primarily due to readout dark current. "Bad columns" are vertical white trails of excess charge deposited by hot pixels during readout. At left, we zoom in on two corners of the quadrant. The leftmost 24 columns are physical "pre-scan" columns that are not charge-collecting, and thus insensitive to dark current. All other "science" pixels exhibit higher levels and more noise than the pre-scan pixels. These differences increase with distance from the amplifier.
**Figure 2:** Superbias image `y2k0235jj_bia.fits` created by combining 24 full-frame raw bias images obtained during one anneal cycle, including `jcfuf5wlq_raw.fits` from Figure 1. Superbias images are free of cosmic rays and have significantly reduced read noise and horizontal bias striping. The 2D gradients (ACS ISR 1202-02) are partially due to the detector and partially due to readout dark.
2. The Pre-scan Wedge

The zoom boxes of Figure 1 show a charge difference between the pre-scan and science pixels in a bias image. This difference increases with distance from the readout row (the serial register). We refer to this increasing difference as the "wedge" which we plot in Figure 3. We compare the averages of the last 4 pre-scan columns (21-24) and the first 4 science columns (25-) unaffected by hot pixels. We avoid pre-scan columns 1-20 to allow for settling of the electronics after each parallel shift (charge transfers among rows). In the science columns, cosmic rays and hot pixels are visible as spikes in the data. We remove those from our subsequent analyses as follows.

We identify bad columns as having excess charge (NMAD\(^3\) 3σ outliers) in the virtual overscan rows. We reject these columns from our analysis, selecting instead the first four science columns unaffected by hot pixels. From each of these science columns, we subtract the averaged pre-scan column. This removes bias striping (ACS ISR 2011-05) and yields four measurements of the wedge for each of the 2048 science rows.

We repeat this analysis for bias images grouped by anneal cycle. We discard the first four bias images of each anneal cycle to again allow for settling of the electronics. So for example, 48 bias images were obtained between anneals dated 2014-01-17 and 2014-02-13. Analyzing the last 44 bias images yields \(44 \times 4 = 176\) measurements of the wedge for each of the 2048 science rows during that anneal period. We then reject cosmic rays as NMAD 3σ outliers from all wedge measurements during that anneal cycle \((176 \times 2048 = 360,448\) measurements in our example). We convert observed data units (DN) to electrons using Table 1, given the commanded GAIN value of 2 e- / DN.

We perform a linear fit on the remaining measurements as a function of distance from the amplifier, as shown in Figure 4. We take the endpoints of this linear fit as the wedge values closest to and furthest from that amplifier's serial register readout row during that anneal period. We converted measured data units (DN) to electrons using the GAIN values in Table 1.

During our example anneal cycle, the wedge is 1.5 electrons in the readout row and 5.7 electrons furthest from it. Dark current contributes the 4.2 electron difference. This dark current contribution has increased over the lifetime of ACS as shown in Figure 5. In this figure, we compare the last 4 pre-scan columns (21-24) to the last 4 science columns (2045-2048) rather than the first 4 science columns without hot pixels. This yields a similar but more stable result, as the underlying bias gradient is much shallower here. In the next section, we show the wedge is consistent with the noise increase measured across the detector.

\(^3\) We use the normalized median absolute deviation (NMAD(x) = 1.4826 median( | x - median(x) | ) as a more robust measure of standard deviation \(\sigma\) (less susceptible to outliers).
Table 1: Gain value of each ACS/WFC amplifier when commanded with GAIN=2, before and after SM4. (From the ACS Instrument Handbook for Cycle 22, Table 4.1.)

<table>
<thead>
<tr>
<th>Measured gain [e-/ DN] in GAIN=2 mode</th>
<th>WFC1 A</th>
<th>WFC1 B</th>
<th>WFC2 C</th>
<th>WFC2 D</th>
</tr>
</thead>
<tbody>
<tr>
<td>pre-SM4 (Mar 2002 - Jan 2007)</td>
<td>2.002</td>
<td>1.945</td>
<td>2.028</td>
<td>1.994</td>
</tr>
<tr>
<td>post-SM4 (May 2009 - present)</td>
<td>2.020</td>
<td>1.886</td>
<td>2.017</td>
<td>2.011</td>
</tr>
</tbody>
</table>

Figure 3: The "wedge" measured in the amplifier C quadrant of the raw bias image jcfuf5w1q shown in Figure 1. We plot the average of 4 pre-scan columns (21-24) and 10 science columns (25-34) each versus distance from the serial register (readout row). The difference between the two increases with distance from the serial register due to readout dark current.
**Figure 4:** "Wedge" measured in quadrant C of the last 44 raw bias images (discarding the first 4) obtained after the January 17, 2014 anneal. The median and 3-σ (NMAD) deviations of the $44 \times 4 \times 2048$ measurements are plotted as red lines. Measurements falling outside this region (including cosmic rays) are discarded (red points). The remaining majority is binned for plotting purposes here as the white-cyan-black density map. Our linear fit to these (unbinned) data yields the dashed white and blue line. The result is a 1.5 electron wedge closest to the amplifier rising to 5.7 electrons furthest from the amplifier. Dark current contributes the 4.2 electron difference.
Figure 5: Wedge increase across the detector over the history of ACS/WFC. Effectively, these are the average numbers of dark current electrons accumulated during readout. These numbers have generally increased over time due to increased numbers of hot pixels (with the exception of the 2006 temperature switch from -77°C to -81°C associated with the switch to side 2 electronics).

3. Read Noise

The ACS/WFC CCD read noise is relatively low, such that the sensitivities of most observations are limited by sky backgrounds, not read noise. Only images with very short exposure times and/or narrow band filters may be read noise limited.

In ACS TIR 2013-02, we measured the read noise history of ACS/WFC over the lifetime of the instrument. Briefly, we differenced pairs of consecutive bias images to remove the 2D gradient (increasing the noise by \(\sqrt{2}\), which we factored out in the end). We measured and subtracted bias striping. We also identified and masked out cosmic rays before finally measuring the noise in each row of the image.

Each quadrant has a slightly different read noise which has remained relatively stable except for a few discrete jumps over the lifetime of the instrument (Figure 6). Shortly after installation in 2002, read noise levels measured between 5 and 6 electrons RMS. After new electronics were installed during Servicing Mission 4 (SM4), read noise levels dropped to between 3.5 and 4.4 electrons RMS. In early 2013 the quadrant D read noise recently jumped up to 5.0 electrons.
RMS, where it remains to this day. Two other such glitches were observed over the lifetime of the instrument; all were likely caused by cosmic ray damage to the on-chip amplifier electronics.

We measure read noise within each quadrant closest to the readout amplifier. Further from the amplifiers, readout dark contributes to the measured noise. We plot this rising noise level as a function of readout row in Figure 7. We perform linear fits and take the endpoints as the values measured closest to and furthest from the amplifier.\(^4\) The former (pure read noise) were plotted in Figure 6. The latter (read + readout dark noise) are plotted in Figure 8.

Read noise and readout dark noise add in quadrature. So by differencing the squares of Figures 6 and 8, we can isolate and measure the noise due to the readout dark (Figure 9). Importantly, we find the lifetime readout dark levels measured due to increased noise are consistent with those measured in the wedge (Figure 5).

**Figure 6:** Complete read noise history of ACS WFC. We measured these values in differenced bias frames taken regularly over the lifetime of ACS to date: between December 17, 2002 and June 6, 2014. Amplifiers A (blue) and B (cyan) read out the WFC1 CCD; amplifiers C (red) and D (magenta) read out the WFC2 CCD.

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\(^4\) This is not guaranteed to be linear a priori, so we also repeat our measurements without linear fitting, instead taking averages of the first and last 10 rows. These results are perfectly consistent with the linear fitting results but with larger scatter, as fewer data points are being considered.
Figure 7: Noise measured along each row of raw bias frames obtained on April 7, 2014. This noise level increases with distance from the amplifier due to readout dark.

Figure 8: Combined noise due to read noise and readout dark in each ACS/WFC quadrant over the lifetime of the instrument. These values are measured furthest from the amplifiers in calibration bias frames obtained regularly over the lifetime of ACS to date.
4. Readout Dark Model

In the previous sections, we analyzed bias images to measure the increased numbers of electrons (§2) and noise (§3) due to readout dark, finding the two to be consistent. Here we show these measurements are also consistent with simulations of readout timing convolved with the per-pixel dark current as measured from 1,000-second dark exposures.

The ACS Daily Monitor Programs have obtained both bias (zero-second exposure) and dark (1,000-second exposure) images over the lifetime of ACS, originally daily and now 3-4 times per week. Figure 10 shows a portion of one such raw dark image (jcfucpqmq obtained December 18, 2013) along with a "superdark" before and after CTE correction. Superdarks are combinations of 20-30 dark images obtained over a 2-week period (ACS ISR 2004-07). The CTE-corrected superdark provides the best representation of the dark current released by each pixel, including "hot" and "warm" pixels which generate dark current at significantly higher rates than other pixels.

Figure 9: Readout dark Poisson variance, measured as a function of time, for the four ACS WFC amplifiers. Readout dark noise and read noise add in quadrature, so here we plot the difference of the variances (noise squared) measured closest to and furthest from the amplifiers (previous figure). Over time, radiation damage has produced more warm and hot pixels, increasing the readout dark.
Readout dark accrues as charge packets are transferred toward the serial register across these physical pixels, each of which generates some level of dark current. Four amplifiers each read out one quarter of the ACS detector. In the row closest to the readout amplifier, each of the 24 pre-scan columns and 2,048 science columns is read out in turn, taking 22 microseconds each (45.6 milliseconds total). Then all rows are transferred one row closer to readout, taking 3.212 milliseconds. This process is repeated for all 2048 rows and then 20 extra times ("virtual overscan"), taking about 100 seconds to read out the full ACS/WFC detector.

We simulated this readout process, allowing dark current (as observed in a superdark) to leak into each pixel as it progresses toward readout. We show the result in Figure 11. Hot and warm pixels deposit excess charge in each "upstream" charge packet as it passes along on its way down to the serial register, leaving vertical trails in the image.

The deposition of dark current is Poissonian, so we add Poisson noise (middle panel). We then also add a Gaussian read noise uniformly to the image. In this example, we show 4 electrons RMS. In Figure 12, we show the resulting total noise in each row. The noise increases with distance from the amplifier as observed in a real bias image (Figure 7).

We repeat these simulations using the real read noise levels and superdarks over the full history of ACS. First we simplify the read noise history to a series of constant values with discrete jumps as shown in Figure 13. We then simulate readout dark based on actual superdarks and add Gaussian read noise to produce (simplified) simulated raw bias images. Finally we measure the noise furthest from the readout row and compare (Figure 14) the results to those measured in real data (Figure 8).

Our simulated bias images (based on the observed history of read noise and superdarks) have noise furthest from the amplifier (consisting of both read noise and readout dark) consistent with that measured in real bias images. We slightly underestimate (by up to 3%) the noise post-SM4, likely due to our simulation omitting the post-SM4 bias-striping 1/f-noise.
Figure 10: Portions of a raw dark frame, superdark, and CTE-corrected superdark. Shown are half of each quadrant read out by WFC2 amplifier C. A superdark calibration image is a combination of 20 - 30 dark images obtained over a two week period. Shown here is the superdark y171245rj comprised of 28 darks, including jcfucqpmq, obtained between December 6 - 20, 2013. The superdark USEAFTER date is Dec. 20, 2013, meaning it should be used to calibrate images obtained soon after that date.
**Figure 11:** We model readout dark as a convolution of a CTE-corrected superdark through the readout process. Each warm / hot pixel leaves a vertical trail as it deposits extra dark current into all data shifting downward through it. We add Poissonian noise to realize integer numbers of electrons. More significantly, we then add uniform Gaussian read noise of some number of electrons (as measured in ACS images). This final image somewhat resembles a raw bias image (Figure 1), but lacking an intrinsic 2D gradient, bias striping (in post-SM4 images), cosmic rays, and CTE. Here, we add 4 electrons RMS read noise to readout dark generated from the superdark y171245qj.
Figure 12: Noise measured along each row of a simulated raw bias image with a Gaussian read noise of 4 electrons RMS and readout dark based on the dark current observed in the CTE-corrected superdark $y171245qj_dk$_. The noise increases with distance from the amplifier due to readout dark as observed in real raw bias images (Figure 7).

Figure 13: Read noise history modeled as constant with discrete jumps (dashed black lines). We use these values as input for our bias image simulator.
Figure 14: Our simulated bias images (including read noise + readout dark) reproduce the history of noise measurements furthest from the ACS amplifiers. Post-SM4 noise measurements are up to 3% higher than our models, which may be attributable to the lack of bias striping (and removal) in our models.

5. Future Implementation

Now that we have quantified readout dark, we will work toward treating it as a separate component in ACS image processing. Our simulations of the readout dark profile reassuringly agree with the measured charge- and noise-gradients across bias exposures throughout the history of the ACS/WFC CCDs. The "bad columns" of readout dark are caused by the worst of the CCD hot pixels. If these hottest pixels are stable on timescales of at least several days, the currently rejected bad columns should still be usable, albeit noisier. With slight modifications, our simulator may also refine the pixel-based CTE correction algorithm by estimating the extra trap-filling electrons provided by readout dark. If we can demonstrate significant improvements, then we will implement these changes in CALACS.
References

ACS Instrument Science Reports (ISRs): http://www.stsci.edu/hst/acs/documents/isrs


