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Post-SM4 ACS/WFC Bias I: The Read Noise History

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ABSTRACT

We report on the read noise history of the ACS/WFC readout amplifiers since the repair of the instrument during Servicing Mission 4 in May 2009. We find that readout amplifiers B and C remain well-behaved with a slow increase in the read noise of approximately 0.0035–0.0048 electrons per year. Amplifiers A and D (since its read noise anomaly in January 2013) exhibited periods of instability in read noise with infrequent jumps of several hundredths of an electron, faster than typical increases, and occasional decreases in noise over prolonged periods. We also investigate for the first time the read noise of the ACS/WFC subarray modes both before and after the change to the subarray format in Cycle 24. We find that the subarray modes prior to Cycle 24 had systematically higher read noise values, and the read noise was inversely proportionate to the size of the subarray, i.e., smaller subarrays had higher read noise. After the changes to the subarray readout patterns in Cycle 24, the read noise values in subarray readouts match the full-frame.

1 Introduction

The Advanced Camera for Surveys (ACS) CCD Electronics Box Replacement (CEB-R) was installed during the repair of the instrument as part of Servicing Mission 4 (SM4) in May 2009. The ACS Wide Field Channel (WFC) readout amplifiers have low read noise values ($3.7 - 5.0\ e^{-}$ post-SM4; Golimowski et al. 2011; Coe et al. 2013), which is critical for accurate photometry of faint sources. Following the installation of the CEB-R, the correlated double sampling mode was switched from its pre-SM4 method of "clamp & sample" to a method called "dual-slope integration," which resulted in an overall reduction in read noise of approximately 25% compared to pre-SM4 values. After Servicing Mission Observatory Verification (SMOV) and the Optimization Campaign (Golimowski et al., 2011), only one report of the ACS/WFC read noise was published following an anomaly in which the read noise of amplifier D increased by approximately 1.2 e^{-} over several weeks in early 2013, finally stabilizing around 5.05 e^{-} (Coe et al., 2013). Despite this anomaly, the read noise in amplifier D remained lower than its pre-SM4 value of approximately 5.2 e^{-}. The increase in the read noise of amplifier D was similar to an anomaly observed in amplifier A in June 2003, in which the read noise increased by approximately 0.8 e^{-} after several weeks of settling. Coe et al. (2013) hypothesized that the cause of the anomalies in both amplifiers was due to damage caused by a heavy ion impact to the silicon lattice of the CCD near the readout electronics.

Following SM4, several properties of the WFC detector were found to have changed due to the use of the dual-slope integration method. One consequence of dual-slope integration was a dependence of the 2-D bias structure on the clocking rate (Golimowski et al., 2017). Prior to Cycle 24, the ACS/WFC subarray readout modes did not have clocking rates identical to the full-frame readout. In particular, pixels within the subarray readout pattern were clocked at the same rate as the full-frame readout, while pixels outside the desired subarray were clocked at faster rates. Additionally, all 4144 pixels in each row of the subarray were read out through a single amplifier with the values of the undesired pixels in the row being discarded. Beginning in October 2009, additional bias images in various subarray patterns were imaged to correctly bias-subtract subarray science observations. A change to the flight software in February 2016 (and implemented later that year at the start of Cycle 24) defined new subarray readout patterns that matched the clocking rates to that of the full-frame by using a "split-serial" readout identical to the full-frame wherein only half of the pixels in a given row are read out through an amplifier (Golimowski et al., 2017).

In this report, we investigate the history of ACS/WFC read noise between SM4 and 2019 Jan 02, which is the date of the first anneal in 2019. In addition to exploring the general behavior of the read noise in the readout amplifiers, we also examine the read noise properties of ACS/WFC subarray images. In particular, the variable nature of the pre-Cycle 24 subarray clock rates may have impacted the read noise of subarray data, therefore we have included these readout modes in our analysis. We describe the data and analysis methods used in this study in Section 2. We present our results in Section 3, and we summarize our conclusions in Section 4.

2 Data & Analysis

Bias images are used to estimate the read noise level in CCDs. To examine the post-SM4 read noise history, we retrieved every post-SM4 bias frame from the CCD Daily Monitor calibration programs. These calibration programs were responsible for acquiring data used to make superbias and superdark reference files for use in the ACS data reduction pipeline. Bias images were obtained four times per day every Monday, Wednesday, and Friday between SM4 and 2015 Jan 15. After this date, the number of bias images was reduced to two every

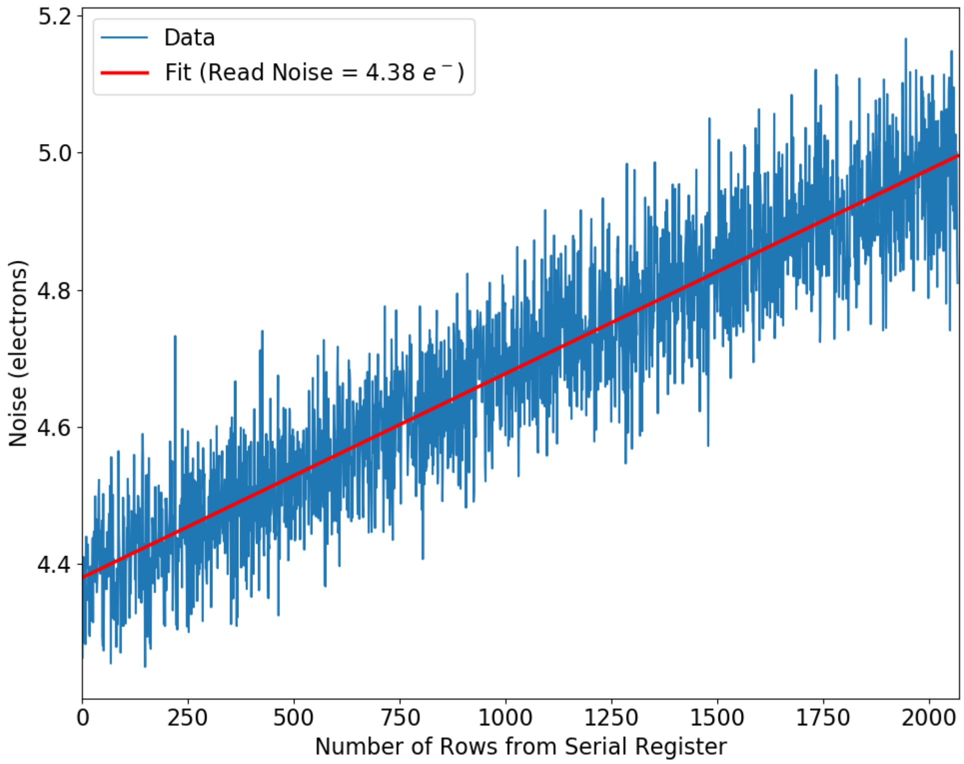

Figure 1: The fit to the noise as a function of row number (increasing away from the serial register) for readout amplifier A. The positive correlation between noise and row number is due to the presence of dark current accumulated during the readout of the WFC CCDs. Read noise values reported here and in calibration files are the intercepts of the fits at row 0.

Monday, Wednesday, and Friday to accommodate new post-flashed short darks without increasing the required number of orbits. Before Cycle 24, subarray bias images were obtained either on an as-needed basis by the instrument team, as part of GO programs, or on a regular basis for a select subset of subarray modes. Beginning in Cycle 24, subarray bias frames were no longer acquired outside of one calibration program (see next paragraph). Between SM4 and 2019 Jan 02, 1,185 full-frame bias images and 1,576 subarray biases were acquired in 30 CCD Daily Monitor programs. Following SM4, interruptions in ACS operations, and thus bias image acquisition, were infrequent and often lasted several days. However, between 2018 Oct 05 and 2018 Oct 27 no bias images were taken for an extended period due to the loss of *HST* gyro-2 and the subsequent switch to gyro-3.

In addition to the subarray bias images taken by the CCD Daily Monitor programs, we also included 48 subarray bias images from *HST* program 14410 (PI: Golimowski) that tested the new subarray readout patterns implemented in Cycle 24 (see Golimowski et al. 2017 for more information). For each 512, 1K, and 2K subarray pattern, four bias images were taken for each WFC readout amplifier. These data provided a useful comparison to evaluate how changes in the readout pattern and clock rate affected ACS/WFC subarray read noise values.

The read noise was calculated from the difference of two bias images. For each readout amplifier, we subtracted two contemporaneous bias images (the "difference image") to remove coherent bias-structure that could artificially inflate our read noise estimate. Subarray bias images were only differenced with other subarray bias images of the same readout pattern to prevent differences in clock rates impacting the results. While bias images are by definition zero second exposures, the readout time of the WFC CCDs is long (100.9 seconds; Golimowski et al. 2017) and therefore there is a non-negligible likelihood that a cosmic ray will strike the CCDs during readout. To remove cosmic rays from our data, we mimicked the behavior of `ACSREJ` (the cosmic ray rejection algorithm for ACS "CR-SPLIT" observations). We performed three passes of sigma-clipping on the absolute value of the difference image and masked features above 6.5, 5.5, and 4.5-sigma above the median using the `astropy.stats.sigma_clip` function. We then grew these masks by a radius of 3 pixels using the scikit-image function `skimage.morphology.dilation`. Growing the masks ensured that we excluded any signal from a cosmic ray that may have spilled into adjacent pixels.

When measuring the read noise of the WFC CCDs, we found that the noise was positively correlated with row number increasing from the serial register. We attributed the bulk of this noise increase to the readout dark current (see Coe & Grogin 2014, Ryon et al. 2017), which is the dark current accumulated during the 100.9 seconds required to read out the WFC CCDs. Rows farther from the serial register accumulate more dark current before being read out, and thus have a larger Poisson error term. While the signal from the readout dark current was removed by differencing bias frames, the noise associated with it remained in the data. Figure 1 shows an example of the fit to the noise from readout amplifier A for reference.

3 Results

Stability of the Post-SM4 Read Noise

Figure 2 shows the read noise as a function of time for the period after SM4 until 2019 Jan 02. From the figure, we made two assessments: 1) the measured read noise systematically increased since SM4; and 2) readout amplifiers B, C, and D (pre-anomaly) were relatively well-behaved, while amplifiers A and D (post-anomaly) were punctuated by infrequent, rapid, low-amplitude changes in read noise. In addition to these fluctuations in read noise, amplifiers A and D also had a larger scatter in read noise measurements relative to amplifiers B and C.

To illustrate the less stable behavior in readout amplifiers A and D, we have plotted the read noise as a function of time for these amplifiers in Figures 3 and 4, respectively, using a finer temporal resolution. Periods of marked instability were identified by eye and shaded for reference. During these unstable periods, the read noise was observed to jump between discrete levels at anneal boundaries, increase much faster than in other periods, or even decrease. In the case of amplifier A, the read noise in early 2019 only just returned to its value following SM4. For amplifier D, the read noise in early 2019 was still slightly below its value following the anomaly in 2013. We also note that the unstable behavior in the amplifier D read noise was at a much lower amplitude compared to amplifier A. The fact that both of these amplifiers had a ~ 1 e^- jump in read noise during their lifetimes gave rise to the

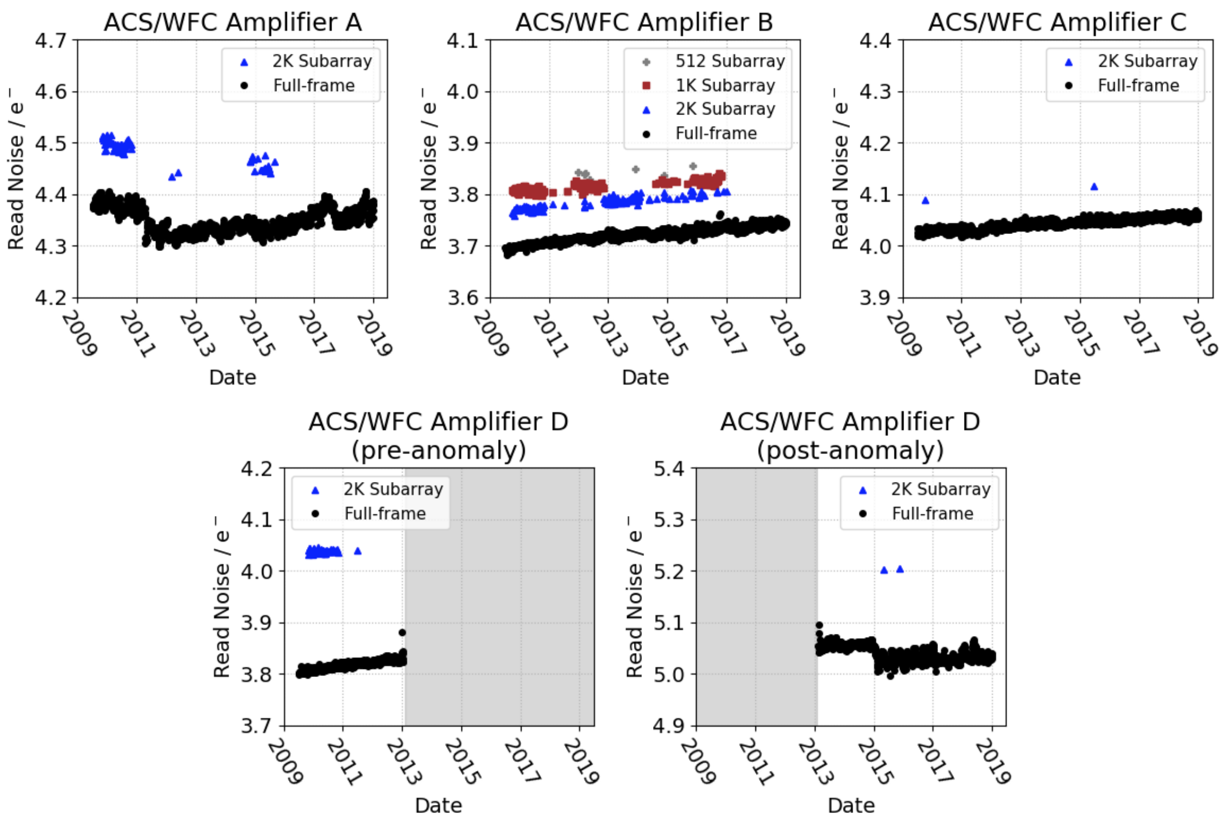

Figure 2: The read noise value in electrons as a function of date measured since SM4. Data are time averaged into 1-day bins for clarity. For each panel, the full-frame and available subarray readout patterns are shown. The scale of the y-axis in each panel is identical to show the relative behavior of the read noise between the different amplifiers. Note that for readout amplifier D, the anomaly in early 2013 (Coe et al., 2013) caused the read noise to increase to a value larger than the maximum value on the y-axis, therefore we have separated amplifier D into two panels to show the pre- and post-anomaly read noise history. The gray shaded regions in the amplifier D panels represent the time period shown by the other panel.

hypothesis that a common event, e.g., a high-energy particle impact on the electronics, was to blame. That the long-term behavior observed in amplifier D matches amplifier A, though to a lesser amplitude, gives more credence to the common event hypothesis.

We fitted first-order polynomials to the read noise as a function of time to estimate its growth. The growth in the read noise is likely attributable to several factors such as the steady increase of the dark rate, decline in the CTE, and degradation of the electronics with age. Khandrika & Baggett (2015) and Khandrika (2017) reported that the WFC3/UVIS CCDs also exhibit a linear growth in the read noise with time, though at approximately twice the rate of the ACS/WFC CCDs. Table 1 shows the fits to the read noise for the four ACS/WFC readout amplifiers. Consulting Figures 3 and 4, we chose suitable time periods to fit for the less well-behaved amplifiers. For amplifier A, we chose a relatively stable period between 2012 Feb 01 and 2016 Nov 01 to estimate the read noise growth. For amplifier D after January 2013, we averaged the results of fitting two stable periods between 2013 Mar 01 – 2015 Jan 15 and 2017 Feb 05 – 2017 Dec 01. The result for post-2013 amplifier D was consistent with zero growth, therefore it is likely that even during apparently stable

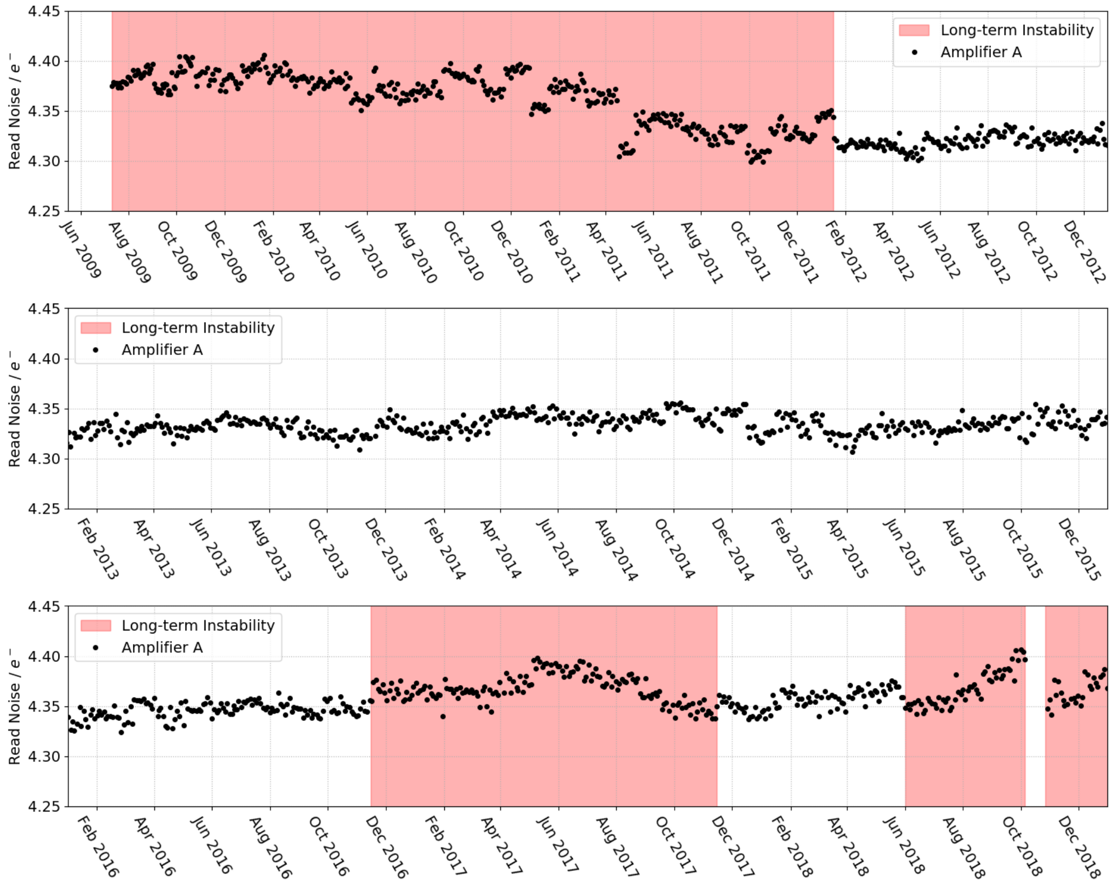

Figure 3: Expanded plot of the read noise as a function of time for readout amplifier A. The y-axis values on each panel are identical. Periods of markedly unstable behavior in the read noise have been shaded in red.

Table 1: Read Noise Growth Fit Parameters

Amplifier	Intercept (e^-)	Slope (e^- / year)
A[a]	3.4163	0.0059
B	2.9747	0.0048
C	3.4957	0.0035
D[b]	2.6115	0.0079
D[c]	5.0245	0.0001

[a] Measured during a relatively stable period between 2012 Feb 01 – 2016 Nov 01. See Figure 3 for reference.

[b] Fit to the pre-anomaly data measured between SM4 and 2013 Jan 01.

[c] Average of the polynomial coefficients fit to two stable periods between 2013 Mar 01 – 2015 Jan 15 and 2017 Feb 05 – 2017 Dec 01. See Figure 4 for reference.

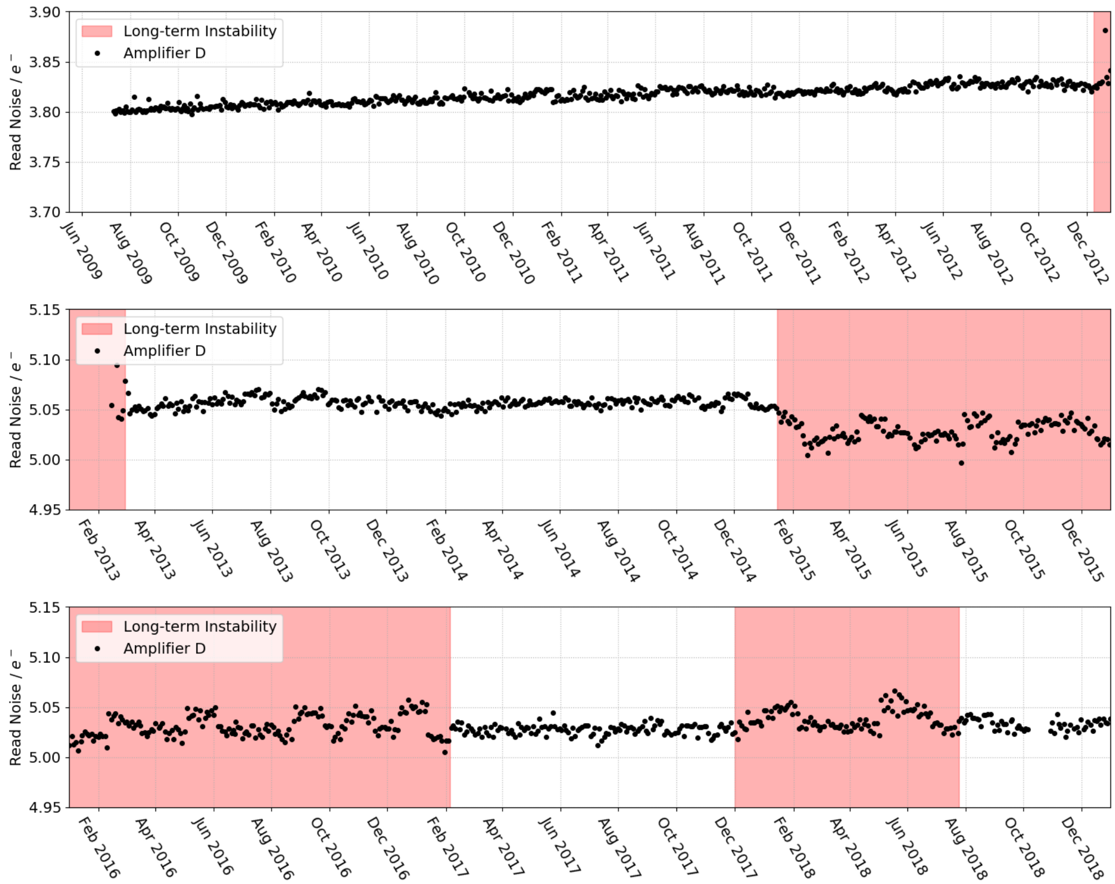

Figure 4: The same as in Figure 3, but for readout amplifier D. The y-axis limits in the top panel reflect read noise values before the anomaly in January 2013, while the middle and bottom panels have limits consistent with post-anomaly values. The scale of y-axis in all panels of Figures 3 and 4 is the same for comparison.

periods the read noise is still erratic.

Assuming that the growth rates will remain steady, we estimated the read noise out to a future date. The analysis of amplifier D suggests that the growth rate of amplifier A may also be inaccurate, though in the absence of more robust data, we adopt the slope of the fit to the amplifier A values. For amplifier D, we assumed that the growth rate before the anomaly in January 2013 was more representative of the actual increase in the read noise with time. With these assumptions, by 2025 Jan 01 we estimated that the read noise will have increased by only 1.3–2.1% since SM4[1].

Subarray Read Noise

As previously discussed in Section 1, the subarray readout patterns prior to Cycle 24 read all pixels in a given row through a single amplifier (rather than the "split-serial" readout used by the full-frame). Additionally, pixels outside of the subarray were clocked at a faster rate compared to the full-frame readout (see Golimowski et al. 2017 for more information). In Figure 2, we have also plotted the read noise measured from subarray images obtained between SM4 and the beginning of Cycle 24 in October 2017. The subarray read noise values prior to Cycle 24 were systematically higher than the full-frame readout (we discuss the post-Cycle 24 subarrays below).

Due to the frequent use of amplifier B for subarray observations, we had sufficient data to show that the subarray read noise before Cycle 24 was inversely proportional to the size of the subarray pattern. For the pre-Cycle 24 period, we only had access to 2K subarray observations for amplifiers A, C, and D. Table 2 shows the offset between the subarray readout patterns and the full-frame using contemporaneous measurements. For amplifier B, the read noise in the 512, 1K, and 2K subarrays was 3.3%, 3.0%, and 1.9% higher, respectively, compared to the full-frame. For readout amplifiers A, C, and D we found offsets in the read noise between the full-frame and the 2K subarray readout of 2.8%, 1.7%, and 5.8%, respectively.

Table 3 shows the read noise values for the post-Cycle 24 subarray formats compared to the full-frame readout. The full-frame values are the average of full-frame bias images obtained at the same time as the subarray test data on 2016 May 09. The updates to the subarray readout modes after Cycle 24 brought the read noise of those modes into agreement with the full-frame.

4 Conclusion

We have examined the read noise history of the ACS/WFC readout amplifiers since the ACS repair during SM4 in May 2009. We found that the read noise values of amplifiers B and C were very stable with a positive trend in growth of 0.0035 and 0.0048 electrons per year, respectively. Amplifiers A and D (since its anomaly in January 2013) have instability, in which read noise has varied by approximately 0.05–1.0 e^-. The instrument team will

[1]For Amplifier D, the increase is 1.9% since 2013 Mar 01 when the read noise stabilized following the January 2013 anomaly.

Table 2: Pre-Cycle 24 Subarray Read Noise Comparison

Amplifier	Date(s)	Full (e^-)	2K (e^-)	1K (e^-)	512 (e^-)
A	2012 May 16 – 2012 May 24	4.32	4.44	···	···
B	2012 Mar 07 – 2012 May 24	3.71	3.78	3.82	3.84
C	2015 Jun 22 – 2015 Jun 28	4.05	4.12	···	···
D	2009 Nov 01 – 2010 Nov 01	3.81	4.03	···	···

Table 3: Post-Cycle 24 Subarray Read Noise Comparison

Amplifier	Full (e^-)	2K (e^-)	1K (e^-)	512 (e^-)
A	4.35	4.36	4.35	4.35
B	3.73	3.75	3.74	3.74
C	4.05	4.06	4.06	4.07
D	5.04	5.07	5.06	5.06

continue to monitor the read noise of the read out amplifiers and assess the need for updates to read noise values in calibration files.

We also investigated the read noise properties of the ACS/WFC subarray modes both before and after changes to the subarray readout definitions in Cycle 24. Prior to the subarray changes, we found that the read noise was systematically higher compared to the full-frame with an inverse correlation between read noise and subarray size. Offsets in the read noise between subarrays and the full-frame were found to be typically 2–3%, however amplifier D showed offsets of as much as 5.8% for the 2K subarray. Since the update to the subarrays to use the split-serial readout like the full-frame, the read noise of the subarray modes have matched the full-frame values.

The read noise values of the four WFC readout amplifiers are stored in the `CCDTAB` reference file for use in the ACS data calibration pipeline (`CALACS`). Currently, a single set of read noise values are used for each gain setting as the time-evolution has been gradual enough, and the differences between subarray and full-frame readouts has been small (or zero after Cycle 24). The ACS team will continue to monitor changes in the read noise and update the `CCDTAB` reference file as necessary.

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