Remeasuring the ACS/WFC Absolute Gains

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Abstract

We measure the absolute gains of the ACS/WFC readout amplifiers for the first time since Servicing Mission 4 (SM4) in 2009. Due to effects now known to be present in post-SM4 ACS observations, but which were either unknown or not well-calibrated at the time, we also recalculate the absolute gains from the Servicing Mission Observatory Verification (SMOV) period immediately after SM4 using a subset of the original data. At the 95% confidence level, we find that the gains measured from data obtained in 2017 match those from SMOV data within the uncertainties.

1 Introduction

The readout amplifier gains of the ACS/WFC CCDs were last measured as part of the Servicing Mission Observatory Verification (SMOV) after the installation of the CCD Electronics Box Replacement (CEB-R) during Servicing Mission 4 (SM4) in May 2009. While in Low Earth Orbit, the ACS CCDs and electronics are continuously bombarded by ambient radiation. This environment is known to have a degrading effect on several properties of CCD performance. It is therefore prudent to remeasure the absolute gains of the four WFC readout amplifiers to ensure that the WFC calibration is robust.

In this study, we make use of the photon transfer curve (PTC) method to measure the ACS/WFC readout amplifier absolute gains. This same procedure was used in the initial calibration of the WFC CCDs from ground test data.
and during the optimization campaign following the successful repair of the ACS/WFC detector during SM4 (Golimowski et al., 2011). A full description of the photon transfer technique is provided in a later section. Here we make the distinction between absolute and “relative” gain. Other reports (Bohlin et al., 2002, 2009) have repartitioned the absolute gains into relative gains by matching signal levels between both the readout amplifier regions and the CCDs in an effort to increase the level of accuracy to $\sim 0.1\%$. It is the relative gains that are used by the ACS data pipeline to transform images from units of data numbers (DNs) to photoelectrons. However, as the relative gains are inherently related to the absolute gains, a first logical step in the verification of the ACS/WFC gains is to redetermine the absolute gain values, which is the focus of this report.

In Section 2, we discuss the data used in our determination of the gains. The data calibration and analysis methods used in this study are described in Section 3. In Section 4, we summarize how our results compare with the values determined during SM4 SMOV and make recommendations for the future. Note that the WFC CCDs after SM4 have available commanded gains of 0.5, 1.0, 1.4, and 2.0 $e^-$/DN, but in practice the ACS Team only supports observations taken with the gain commanded to CCDGAIN = 2.0 $e^-$/DN since shortly after SM4. In light of this, we report only on the readout amplifier gains with the commanded gain set to this supported value.

2 Data

The data for the absolute gain analysis were collected from HST program 15393. All data were acquired during a single visit executed on 2017 November 06. The images are pairs of ACS/WFC full-frame observations of the ACS internal tungsten calibration lamp in the F435W filter at five different exposure times ([0.8, 4.4, 8.8, 16.2, 21.4] seconds) with the commanded gain CCDGAIN = 2.0 $e^-$/DN. These exposure times were chosen to sample nearly the full dynamic range of the ACS/WFC CCDs between $2.5 \times 10^3$ and $4 \times 10^4$ DN. The exposure times match closely those used in the SM4 SMOV proposals to measure the gain in June 2009, but we have not included exposures longer than 25 seconds because saturation begins to occur at those signal levels. In SMOV, the longer exposure times were designed to measure the approximate value of the full-well saturation of the ACS/WFC CCDs, but that objective is outside the scope of this experiment. The F435W filter was used both during SMOV and in the 2017 observations because it has the lowest count rates from the tungsten lamp, which allows sampling at low-signal levels.

We also retrieved data from SMOV programs 11809 and 11810 to re-establish the gain immediately after SM4 using the same tools that we use for our 2017 data to provide a direct comparison. We excluded datasets from those programs with signal levels in excess of $\sim 4 \times 10^4$ DN that were used to test the linearity and full-well depths of the CCDs. Due to concerns about the bias calibration and noise properties for different image sizes (see Golimowski et al. 2017; Desjardins & Grogin 2018, in prep.), we only used images taken

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1This report by the ACS instrument group at Johns Hopkins University was previously hosted on their website. At the time of writing, it is no longer accessible, but we include the citation here for completeness.

2Also referred to as analog-to-digital units or ADUs.

3CCDGAIN is the header keyword in ACS FITS files that lists the commanded gain.
with the full-frame readout. For similar reasons, we excluded Extended Pixel Edge Response (EPER) images from our analysis. To match the post-SM4 nominal instrument settings, we selected images taken in the Dual Slope Integrator (DSI) readout mode at the full clock rate with \( \text{CCDGAIN} = 2.0 \ e^-/\text{DN} \). For each proposal, this limited us to two pairs of images, each with 12.5 and 20.5 seconds of exposure time.

A description of the SM4 SMOV observations can be found in Sirianni et al. (2009). The data taken from proposals 11809 and 11810 come from visit A1 for which the various voltage settings were commanded to the pre-failure values in use between July 2006 and January 2007. Golimowski et al. (2011) treat the data from each proposal separately. In this study, we compute our results for SMOV by combining the data from the two programs because we use a smaller subset of data compared to Golimowski et al. (2011). This is done in an effort to increase the accuracy of the measured SMOV gains for comparison to our November 2017 values.

3 Analysis

The PTC method (Janesick et al., 1987) compares the variance of the illuminated pixels in a region to a value representative of the signal in the same region (e.g., the median). At signal levels much larger than the read noise (i.e., in the “shot,” or Poisson, noise regime), the expectation is that the variance in DN is described as \( \sigma^2_{\text{DN}} = G^2n_e \), where \( G \) is the reciprocal gain (i.e., \( G = 1/g \) and has units DN/e\(^-\)) and \( n_e \) is the signal in photoelectrons measured by the readout amplifiers. The signal level in DN is simply \( S_{\text{DN}} = Gn_e \). Treating the variance as a linear function of the signal level, we can write

\[
\sigma^2_{\text{DN}} = mS_{\text{DN}} + b.
\]

If we assume that \( b \approx 0 \), which it should be for a linear CCD with low read noise values (for the ACS/WFC readout amplifiers, the read noise is \( \approx 2 - 3 \ \text{DN} \); Ryon et al., 2018), then

\[
\sigma^2_{\text{DN}} = mS_{\text{DN}} \\
G^2n_e = mGn_e \\
m = G.
\]

Thus, the ACS/WFC gain \( g \) is measured as the inverse slope of the linear fit to the variance as a function of signal.

We calibrated our data using \texttt{calacs} version 10.0.0 (released January 2018). The only image processing applied to the data were the \texttt{BLEVCORR} and \texttt{BIASCORR} steps of the \texttt{acscdd} algorithm. These steps removed the bias level using the bias prescan regions, trimmed the physical prescan and virtual overscan regions from the image, removed the bias striping present in post-SM4 WFC images, and subtracted the remaining 2-D bias structure from the data. Because \texttt{calacs} converts images from DN to photoelectrons, we converted the images back to DN using the gain values contained in the CCDTAB reference file. The dark current was intentionally left in the data as its removal adds unwanted noise into our measurements.
Table 1: Absolute Gains of the ACS/WFC Readout Amplifiers

| Amplifier | \(g_{OC}^a\) | \(g_{2009}^b\) | \(g_{2017}^c\) | \(|g_{2017} - g_{2009}|\) |
|-----------|--------------|--------------|--------------|-----------------|
| A         | 2.09         | 2.06 ± 0.06  | 2.08 ± 0.02  | 0.02 ± 0.06     |
| B         | 1.92         | 1.98 ± 0.06  | 1.92 ± 0.02  | 0.06 ± 0.06     |
| C         | 2.09         | 2.09 ± 0.06  | 2.06 ± 0.02  | 0.03 ± 0.06     |
| D         | 2.05         | 2.08 ± 0.06  | 2.02 ± 0.02  | 0.06 ± 0.06     |

\(a\) Average gain from the two iterations of the SMOV optimization campaign (Golimowski et al., 2011).

\(b\) Gain measured in this study using the combined data from SMOV programs 11809 and 11810.

\(c\) Gain measured from data obtained in November 2017.

Our measurements were made in a 5 × 5 grid of boxes covering each amplifier region, with each box having 40 pixels on a side (see Figure 1). This box size allows for an adequate number of pixels to compute statistics while minimizing the effects of large-scale variations across the CCDs. Boxes were positioned to be no less than 40 pixels from the edges of the CCDs or amplifier boundaries. Before making measurements, we identified and excluded pixels in each box region that were impacted by cosmic rays. Through experimentation, we found that sigma-clipping the data was not sufficient to remove all signal associated with a cosmic ray event. Therefore, we mitigated the effects of cosmic rays in two ways: (1) we removed all pixels with a 5σ deviation from the median of the differenced data using the `astropy.stats.sigma_clip` function (`astropy` version 3.0.4; Astropy Collaboration et al. 2013, 2018), and (2) we grew the cosmic ray masks outward using a 3 pixel radius to account for any signal in adjacent pixels using `skimage.morphology.disk` and `skimage.morphology.dilation` (`scikit-image` version 0.14.0; van der Walt et al. 2014).

We measured the median signal in each box by taking the median of all pixels in the box region in both images in a flat-field pair. The variance was measured in the boxed regions from the differenced image pairs to eliminate fixed pattern noise. We used `numpy` version 1.15.1 (Oliphant 2006) to determine these statistics. We reiterate that our observations are dominated by shot noise, and thus we can ignore the read noise floor in our determination of the gain. It is impossible to illuminate the ACS/WFC CCDs using the internal tungsten lamp to sufficiently low levels such that the data are near the noise floor. We used a robust linear model (RLM) to fit the data using `statsmodels` version 0.9.0. An example fit to the PTC for readout amplifier A is shown in Figure 2.

4 Discussion and Conclusion

A summary of the readout amplifier absolute gains measured from the SM4 SMOV and our November 2017 observations are presented in Table 1. Uncertainties are presented at the 95% confidence level (approximately 2σ). Our redetermination of the gains measured as part of the SM4 SMOV optimization campaign have approximately 3% accuracy, while the newly obtained 2017 observations have 0.8 – 1.1% accuracy. From these measurements, we find that there have been no statistically significant changes in the absolute gains of the...
ACS/WFC readout amplifiers since the repair of the instrument in May 2009.

We emphasize that the measurements presented in this study are the absolute gains of the ACS/WFC readout amplifiers. The gain values used by the calacs pipeline are taken from the CCDETAB reference file, and are based upon the absolute gains with adjustments made to match signal levels both between adjacent readout amplifier regions and the two WFC CCDs (Bohlin et al. 2002, 2009). The gain values in CCDETAB were also corrected for CCD sensitivity based upon observations of the globular cluster NGC 104 (47 Tuc). Therefore, if significant changes in the absolute gains are found, then we must carefully consider the interaction between the gain and the sensitivity of the CCDs.

The stability of the readout amplifier gains over the past 8 years since SM4 is remarkable, particularly in the case of readout amplifier D that suffered a 1.2 e$^-$ (32%) jump in its read noise in January 2013 (Coe et al., 2013). In addition to this anomaly, increases in the dark current rate (Ryon et al., 2018) and numbers of unstable warm/hot pixels (Borncamp et al., 2017), and the degradation of the charge transfer efficiency (Ubeda & Anderson, 2012) are the result of constant bombardment of the CCDs by high-energy particles in the ambient radiation environment. As *Hubble* and ACS continue functioning into the 2020s, careful monitoring of the instrument health and calibration is critical for science programs. To this end, we will begin regularly monitoring the absolute gains of the ACS/WFC readout amplifiers on a yearly cadence.

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**References**


Figure 1: An example image of the tungsten lamp with exposure time 0.8 seconds. This subsection corresponds to the region of the WFC1 detector read out by amplifier A. The white boxes indicate the regions in which we measured the statistics for the PTC. While large scale structure due to thickness variations of the silicon wafer are clearly visible, the boxes are small enough to not be affected.
Figure 2: The PTC for ACS/WFC readout amplifier A measured from data obtained in November 2017. Clusters of data points correspond to the different exposure times used in our 2017 observations. The inverse slope of the linear fit is equal to the absolute gain measured in units of $e^-$/DN.