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ACS-R Multi-Parameter Optimization Constraints

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Abstract

The repaired ACS WFC will undergo a three-week Optimization Campaign during early SMOV with read noise being the primary target for improvements through testing adjustments of a large number of detector control, voltage and timing patterns. A large number of factors, in addition to read noise, contribute to the utility of science data from ACS WFC. In this TIR we enumerate several such factors including Charge Transfer Efficiency (CTE), Full Well Depth (FWD), Linearity, Cross talk, gain stability and bias drift. For each we quantify values that existed when WFC was last used in January 2007 and provide extrapolation that we believe would have existed with a continuously operable instrument to May 2009. For each factor we provide qualitative discussion of how changes would impact science in order to provide a framework for considering changes that may arise during the Optimization Campaign.

In many cases, e.g. for CTE, significant deterioration of performance from nominal expectations as a result of changes during the optimization campaign would provide support for adjusting the optimization to lessen this, even at the cost of some increase of read noise.

1. Introduction

The ACS-R development has been under a very tight schedule since the on-orbit failure in late January 2007. Currently, ACS-R has successfully been designed, built, and thoroughly tested through TV and SMGT under the leadership of Ed Cheng. The ACS-R will utilize the newer technology of sidecar ASIC chips for processing the signals coming off the original CCDs, this offers the prospect of read noise levels that may be considerably better than those available previously. As argued in Gilliland, Sembach and Sirianni (2007) enough of the ACS science program would benefit from lower read noise values to make the currently anticipated improvements very beneficial to science return from the repaired ACS.

Science-grade CCDs for use on Hubble are typically developed with a large number of additional traits that are important for being able to conduct state-of-the-art science observations. In this TIR we explore these additional factors, quantify their values previously and as nominally expected immediately after SM4, and provide guidance on how large changes for any of these would impact the utility of the repaired ACS WFC.

Throughout this TIR we will qualitatively contrast the relative benefit of improving the read noise from a constant on-orbit value of 5.5 e- (for gain = 2 e-/DN) to an anticipated value of 4.0 e- with the ASIC and dual-slope integration with possible degradation in these other factors.

2. Charge Transfer Efficiency

CTE quantifies the amount of charge that is properly transferred along the rows and columns of the CCD during read out. Because charge packets undergo up to 2048+2048 parallel and serial transfers during read out of the WFC, a small deviation from perfect CTE can cause significant photometric losses in a WFC image.

Two ACS calibration programs have been conducted to monitor the on-orbit degradation of WFC CTE due to radiation damage. The first program uses internal lamps and special readout modes to monitor the extended pixel edge response (EPER) of the detector and compare it with laboratory measurements using the same technique. EPER is a measure of the extended tail of charge that is deferred from the illuminated imaging region of the CCD into the trailing physical or virtual overscan. The ACS-R optimization campaign will employ identical EPER tests to allow direct comparison with the results of the long-term monitoring program before January 2007. Mutchler and Sirianni (2005) derived a parametric expression for WFC's parallel CTE based on EPER measurements from March 2002 to November 2004:

$$CTE(s, d) = 1.0 - (5.33e - 5 + 2.65e - 6 * (d - 52335)) * (s^{-0.61}), \tag{1}$$

where s is the imaged-source signal in electrons and d in the Modified Julian Date. (SM3B launched on 1 March 2002 = MJD 52335.)

Reducing the CCD operating temperature in July 2006 yielded improved CTE relative to the extrapolated prediction from Eq. (1). The latest measured and predicted CTE values are given in Table 1.

Table 1: Parallel CTE from EPER, On-orbit experience and projection.

Signal/Date	Jan '07	May '09
1620 e-	0.999949	0.999921

The estimated loss of charge from a flat signal of $1620e^-$ after 1024 parallel transfers (i.e., the center of the CCD) in May 2009 is 0.999921^{1024}, or 7.8%.

The second ACS CTE monitoring program involves the imaging of an external target in both WFC1 and WFC2 to quantify directly the photometric losses from an astronomical source. The program exploits the opposing directions of the parallel charge transfers in WFC1 and WFC2 to record contemporaneous images of a single target field offset by one CCD width between exposures. Using this technique, Riess and Mack (2004) found evidence for a linear degradation of CTE with time, and they quantified this effect in terms of photometric corrections. Using their examples of target fields susceptible to CTE losses (the faint end of the M31 color–magnitude diagram and z=1.5 Type Ia supernovae), we project relative losses of 6% and 10% in January 2007 and May 2009, respectively. A more recent study by Chiaberge (2008) suggests that the WFC CTE losses are both larger and more rapidly degrading than noted by Riess and Mack. If so, then losses of 10% and 15% are expected for the susceptible science fields named above in January 2007 and May 2009. Moreover, the calibrated CTE losses are only accurate to 25%, so systematic uncertainties of 2.5% and 4% must be attached to the January 2007 and May 2009 projections.

The projected photometric losses due to degrading parallel CTE can be accommodated by extensive calibrations and subsequent photometric corrections of the science data. However, the systematic uncertainties are large and increasing. Scientists conducting research in the photometrically sensitive fields (like those named above) would usually accept greater read noise over substantially degraded CTE if given the option. Further degradation of parallel CTE by an amount comparable to that already expected by May

2009 would more than offset the scientific benefits of a $5.5e^-$ to $4.0e^-$ reduction in read noise.

The serial CTE of the ACS WFC has historically been an order of magnitude better than the parallel CTE (by one '9'), so it is difficult to quantify accurately. Any change in the ASIC settings that would alter this situation and would require active calibration and correction of serial CTE losses would have a large negative impact on the quality of ACS science.

CTE is a subtle, nonlinear effect that depends on source signal, background signal, time, and perhaps as yet unidentified conditions. The ability to increase the initial post-SM4 CTE during the optimization campaign, or at least prevent further degradation of the CTE from the nominal expectation, would be very beneficial for ACS science.

3. Full Well Depth

The Full Well Depth (FWD) contributes to available dynamic range of individual exposures which might be defined as the difference between the brightest (set by FWD before saturation) and faintest (limited by high Poisson noise from target and read noise) targets usefully obtained in single exposures. While some science programs, and especially calibration programs obtain data utilizing the full dynamic range offered by the pre-loss ACS WFC, most science is conducted on faint targets for which the FWD is not a relevant factor.

The FWD inherent to the detector pre-repair varies from about 80,000 to 88,000 e- over the WFC field of view. (In gain = 1 e-/DN the upper data values are limited to $2^{16} =$ 65536 e- in the analog to digital conversion.)

The ACS WFC detector pre-repair remained linear well beyond saturation in the sense that point source photometry could be accurately recovered simply by summing the counts recorded in all the pixels that had been bled into. For a small subset of science and calibration programs this ability to utilize extended dynamic range on the high side has been very valuable.

Were the FWD to be significantly decreased post-repair, say by 25% to 60000 e-, instead of the original 80000 e- this would not be seen as damaging to the bulk of science observations. For such modest decreases of FWD, if a trade were available with read noise being measurably improved, it would likely be appropriate to opt for the read noise improvement. While the excellent dynamic range provided by the original ACS WFC was nice to have it only weakly contributed to the bulk of ACS science return.

If the FWD were to both be significantly reduced, and the ability to recover saturated point source photometry to high fidelity were also lost, then this would be a larger impact on science and calibration. We would only trade a significant 5.5 e- to 4 e- improvement of read noise against a drop of FWD to under 40000 e- coupled with loss of ability to perform saturated image photometry.

4. Linearity

The ACS WFC on orbit, with the exception of CTE growth, provided linear response to within our ability to quantify such, typically ∼0.1% (Gilliland 2004). It has been the goal of ACS WFC calibrations to support 1% absolute photometry. In assessing error terms contributing to photometry for ACS WFC pre-repair it has not been considered relevant to take into account any (non-CTE) deviations from perfect linearity.

The onset of non-linearities either at low intensity where much ACS science is conducted, or at high intensities where some science and relatively more calibration is performed would be seen as a large loss for science. The existence of such non-linearities, should such influence the ability to extract photometry at the 1% level would require calibration with the near certainty that, as with CTE, some component of the correction would remain as increased levels of systematic uncertainty. Furthermore, with increasing levels of CTE the need to calibrate out any additional non-linearity depending upon signal level, or accumulation rate would inherently decrease the ability to quantify CTE itself.

Given the option of having near-perfect linearity as existed for ACS WFC pre-repair in trade against even a significant reduction of read noise from 5.5 e- to 4 e- with attendant non-linearity affecting photometry at the 1% or more level, the overall science program would be better served by retaining linearity.

5. Cross talk

Cross talk refers to the imprinting of electronic signatures from source structure within one amplifier into other amplifiers during the over-lapping readouts. For the pre-repair ACS WFC such cross talk was readily noticeable cosmetically with close inspection of images having strong sources in one quadrant. However, the quantitative level was of order 4×10^{-5} in the sense that a source at level of 50000 e- in one quadrant would impart a negative deviation at the affected position in a target quadrant of only 2 e-. Given a read noise of some 5.5 e-, even for the strongest cross-talk effects that go between the two amplifiers on the same CCDs, the per pixel cross talk remained below this level. Only when the source covers many contiguous pixels was the existence of cross talk readily noticeable as minor offsets in the affected amplifier domain. Although the effect was quantified to some extent in the pre-repair era, it was judged to be too small to warrant the thorough investigation necessary to establish correction algorithms. The impact on science was judged to be such that 1% photometric precision was never threatened.

Significantly higher cross talk could be problematic, however. For example, cross talk of order 4×10^{-4} (i.e., 10× worse than previously seen), could impose a 20 e- offset in the CCD quadrants neighboring an imaged source of 50000 e-. This offset is 4 times the read noise and would contribute a 1% photometric error to an affected source of 2000 e- in a neighboring quadrant whose intrinsic Poisson-limited error is 2%. Likewise, this cross talk would contribute a 0.2% error to a 10000 e- source whose intrinsic Poisson error is 1%. At this level of cross talk uncorrected data frames would generally be rather ugly in a cosmetic sense, and induced photometric errors would be on the verge of becoming significant. At this level 4×10^{-4} it would probably be judged necessary to calibrate the effect and apply corrections in pipeline reductions of the data. Depending upon the nature of the cross talk (which may not be simply a linear additive or multiplicative dependence on source, but may have non-linearities and unique amplifier to amplifier differences), establishing correction procedures and calibrations may well be non-trivial.

Given a trade between staying with the pre-repair minimal cross talk and read noise at 5.5 e-, and a much improved read noise of 4.0 e- at a problematic cross talk level of 4×10^{-4} we would want to opt for the pre-repair values.

6. Gain stability

Two lines of evidence pre-repair point to excellent gain stability on all time scales, probably below our ability to quantify such. Since two gain values (1 e-/DN and 2 e-/DN) were supported for routine science use, it was necessary to establish the ratio of gain = 1 to 2 quite accurately such that moving from one to the other would not impart small systematic shifts in photometry. Fortunately this ratio can be measured very precisely by simply taking back-to-back exposures with the same exposure time and filter on a rich star field and ratioing the resulting counts in DN. Gilliland (2004) reported on analysis of such data from early in the mission that corrected the GAIN = 1 to 2 ratio by 0.78 ± 0.01% relative to ground calibration values. Analysis of data taken 2.5 years later in Gilliland (2006) established that this gain ration had remained stable at a formal level of 2 parts per

10,000 with an error in establishing the ratio at this same level. This is some 10× better than levels of change which would even start to be problematic for photometry.

The second line of evidence follows from tracking changes over time where the same star field has been repeatedly observed. Gilliland has done this for science purposes with data densely sampling time scales from 8 minutes to 23 days finding inherent stability to the level of $\lesssim$0.1%. This follows from the ensemble mean counts of stars staying constant to the 1 part in 10^3 level. It is likely that these deviations follow from other uncompensated effects like changes of focus that induce changes in the photometry. Even at the level of 0.1% fluctuations would not yet be a serious problem for photometry, although changes (if real) 10× this would be very serious. The stability on even longer time scales of years is monitored through our standard CCD stability test which observes the same field in 47 Tuc a few times per year and spectrophotometric standards at least once per year. From this monitoring small drifts of about 0.2% per year (Bohlin 2007) are seen. This more likely results from degradation of the overall quantum efficiency than a drift of the gain, but serves as an upper limit on any drift of gain. It is not practical, nor of more than academic interest, to separate sensitivity and gain changes in the minor drift seen on-orbit. Any slow changes in response on timescales of a year or longer are easy to account for in calibrations, and are expected.

Instabilities in the gains would be problematic only if much larger and more rapid than anything seen on-orbit. Observation sets generating time series for many stars that are capable of demonstrating gain changes on short time scales are also self-calibrating for intrinsic science applications. Problems would only arise if gain changes at amplitudes in excess of $\sim$0.2% occur on time scales short (few months) compared to our routine CCD stability monitoring cadence. Changes of this nature are not expected, but if present would constitute a sufficient problem such that in considering the (by now in this TIR) standard trade against substantially reduced read noise of 5.5 to 4 e-, we would opt for choosing stability in the gain.

7. Bias drift

Thermal vacuum testing revealed a drift in the overscan bias level of images read in dual-slope integration mode. This bias drift depends on the intensities of pixels in the imaging area of the CCD. Since the overscan is meant to supply a robust estimate of the bias offset applying globally to an image, any dependence of overscan values on the image itself is problematic unless the effect can be calibrated out to high fidelity. For the amplitude of bias drift seen in the DSI data such a calibration is evidently available that can remove residual effects sufficiently well that impact on science data is acceptable.

In a general sense any bias drift affects that cannot be removed sufficiently well to avoid increased uncertainties in photometry at the level of ∼0.2% would be considered problematic. Review of on-orbit data shows that no bias drift of importance (none at all detectable for uniform image-area illumination at 5000 e-, a minor shift of perhaps 0.02% seen for illuminations at 50000 e-) were present.

8. Dark Current and Hot pixels

Radiation damage on-orbit leads to a continuous growth of permanent hot pixels (defined to be > 0.08 e-/s), and an increase of the mean dark current per pixel.

In January 2007 the fraction of the WFC covered by permanent hot pixels (those not removed in monthly anneals) was 0.68%. The fraction anticipated for May 2009 after application of an anneal is 1.1%. Similarly the mean dark current for January 2007 was at about 10.7 e-/hour, anticipated to have increased to 15 e-/hour in May 2009 from the additional accumulated radiation damage.

While hot pixels are positive events fixed in detector coordinates, the CCDs continuously detect positive events from cosmic rays at random positions passing through the detector at an average rate of 1% to 2% of the area per an average exposure length of about 600 seconds. While there is no hard boundary at which increased hot pixels qualitatively change their impact on science data quality, a reasonable metric would be that when the number of permanent hot pixels reach 2% (not expected until early 2014) and begin to exceed the higher levels of cosmic ray fluence then hot pixels begin to limit science quality. Any step function increase of hot pixels, that is equivalent to a two-year advance in this progression would be seen as more of a loss than the improvement resulting from read noise dropping from 5.5 e- to 4.0 e-.

The typical dark current of 15 e-/hour contributes only 2.5 e- to the background of an average WFC exposure of 600 s. In the most popular broad band filters F606W and F814W the sky level in 600 seconds is typically 60 - 80 e-. The effect of extra dark current is an added Poisson term that combines with the sky background and the square of the read noise in electrons. Even at a read noise of 4 e- the read noise variance term is 16, thus dark current is far below both read noise and sky influences. Only if an order of magnitude increase of the dark current were to occur would this become a serious issue for science. In practice an order of magnitude increase of dark current would likely be accompanied by a comparable increase of warm and hot pixels of more limiting consequence.

9. Other

Any new instrumental performance issue that jeopardizes the ability to reach the goal of 1% absolute photometry would be considered serious. It is easy to hypothesize examples that would be easy to deal with in calibration (a linear drift in gain at 1% per year would be easy), and hard to deal with (randomly fluctuating gains at the level over 1% on time scales ranging from minutes to weeks would be a disaster for being able to reach the desired photometry level). Similarly, were several of the additional factors discussed in this TIR to simultaneously degrade to limits near, but not exceeding the individual thresholds for concern, this would be a potential problem for science quality.

10. Conclusions and Trade Space

A full quantitative assessment of the many factors that routinely come into play for the high fidelity performance of science grade CCDs is well beyond the scope of this study. In this report we have attempted to enumerate many such factors, compare these to their values when ACS WFC was last active in January 2007, project these to May 2009 assuming normal evolution of the detectors, and to discuss in the context of what changes would be acceptable for science.

We settled upon attempting to assess one specific trade-off, which in practice might never be explicitly available, of asking at what level of degraded performance in any area we believe the overall science program would best be served by retaining nominal performance in trade for giving back an otherwise available gain of 5.5 e- to 4.0 e- in read noise. While this is an imperfect metric, the impact of read noise changes on the science program has been quantified (subject to important simplifying assumptions) in TIRs (Gilliland, Sembach and Sirianni 2007 & 2008), and providing qualitative judgments against this based on our collective instrument calibration and extensive science usage experience should be useful for informing future discussions.

Table 2 contains the summary of trades. In all cases the lines include values for January 2007 (measured), May 2009 (projected), and ‘Problematic level’. Problematic level is defined to be that which in our collective judgment would create more problems for the overall ACS WFC science program, than forgoing an otherwise available decrease of read noise from 5.5 e- to 4.0 e-.

Not all entries in Table 2 are of equal priority for likely optimizations. For example, any change of CTE for better or worse will directly impact science capabilities since this is already a limiting factor. The CTE entry is only for parallel transfers, currently the serial values are an order of magnitude better, were serial CTE to decline such that residual corrections need to be tracked (∼1% loss at center, or 0.99999) this also would become an important factor. At the other extreme dark current is not remotely close to being a limiting factor. Entries in Table 2 are ordered with those most likely to be important in optimizing performance at the top.

Table 2: Multi-metric Trades Table

Importance	Metric	January 2007	May 2009	Problematic level
1	Charge Transfer Efficiency	0.999949	0.999921	0.9999[a]
2	Cross talk	4×10^{-5}	4×10^{-5}	4×10^{-4}
3	Non-linearity	<0.1%	<0.1%	0.5%
4	Gain stability	$\lesssim$0.1%	$\lesssim$0.1%	0.2%[b]
5	Bias drift	0.02%	0.02%	0.2%[c]
6	Hot Pixel Fraction	0.68%	1.1%	1.5%
7	Full Well Depth	84000 e-	84000 e-	40000 e- [d]
8	Dark Current	10.7 e-/hr	15 e-/hr	100 e-/hr

[a] For flat field signal of ∼ 1620 e-. Although not expected, any improvement to CTE to higher transfer efficiencies would be of direct and important benefit to science from ACS.

[b] Gain instability at 0.2% on time scales less than several months, larger values benign if on time scale of a year.

[c] This is twice the level seen in Thermal Vac testing.

[d] Drop of FWD to 40000 e- coupled with loss of linearity beyond saturation.

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