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Summary

We summarize our current understanding of the state of the WFC3/UVIS and ACS/WFC CCD Detectors' Charge Transfer Efficiency (CTE) and provide recommendations for planning future observations with these cameras. In particular, due to the declining CTE of these devices a post-flash capability is being supported starting with Cycle 20. This White Paper provides observers with guidance and references to support a decision on the use of this new mode. Further, a correction algorithm is now available within the ACS data processing pipeline and development of a similar algorithm is underway for WFC3. The benefits and limitations of these approaches to the mitigation of the (unavoidable) decline in the CTE of these detectors are discussed.

1. The Issue

The CCD detectors on HST operate by the simple process of converting incoming photons into electron/hole pairs, collecting the electrons in each pixel, and then transferring those electrons across the detector array during the device readout. The transfer process moves each pixel's electrons down along the columns and then across in a transfer register to the amplifier located in the corner of the detector array (see Figure 1). When the detectors were manufactured, these transfers were extremely efficient (typically 0.999996 of each charge packet was transferred successfully from one pixel into the next. Thus for the "worst case" transfer of 2051 shifts down the column for the ACS/WFC and WFC3/UVIS detectors, slightly over 99% of the charge collected in a pixel would be delivered to the transfer register. [Losses in the serial transfer register are smaller and much less important to the topic of this White Paper.] This Charge Transfer Efficiency (CTE) was an important parameter in the design and selection of CCD devices for flight.

Once in space, the flux of energetic particles (especially relativistic protons and electrons during HST's frequent passages through the South Atlantic Anomaly) damages the silicon lattice of the CCD detectors. This creates both "hot" pixels and charge traps. This radiation damage is cumulative and was unavoidable given current technologies for detector construction and shielding.

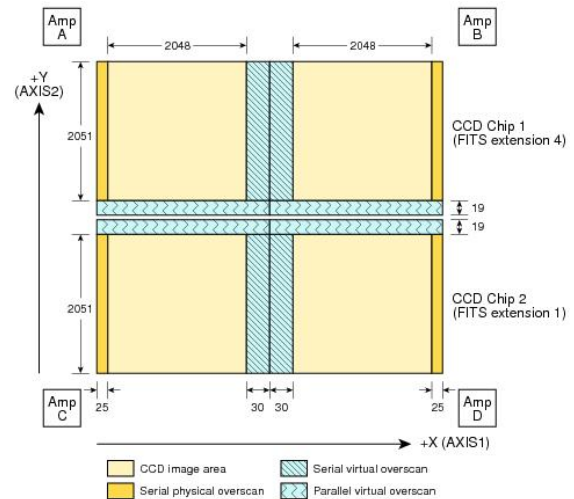


Figure 1: CCD Layout for WFC3/UVIS. Charge is transferred vertically from the center to the top (or bottom) transfer register and then outwards to the appropriate amplifier.

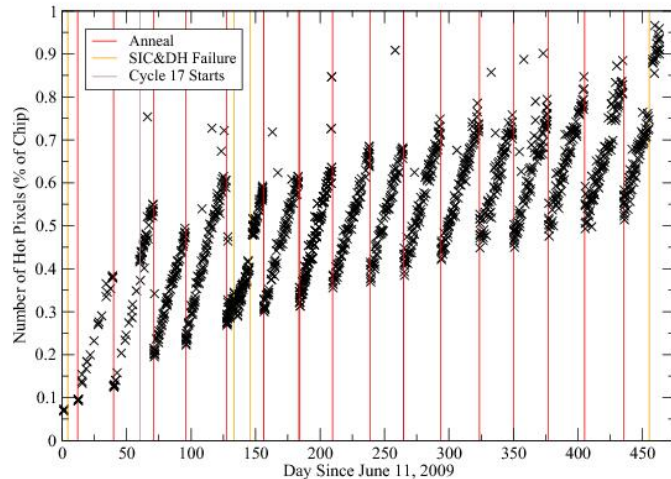


Figure 2: WFC3/UVIS Hot Pixel Statistics. Vertical red lines denote monthly anneals. The partial reduction in the population of hot pixels along with the growth of a permanent population is seen. The apparently faster rise in 2009 is likely due to the higher radiation flux experienced by HST during solar minimum. population of hot pixels (Figure 2).

The hot pixels represent sites of excess charge generation at sites of lattice damage. These can be removed from observations by dithering (shifting the scene slightly on the detector between exposures). Also, STScI obtains daily dark calibration images, which are combined to produce 7 day running average dark frames which provide fairly good identification of hot pixels. These darks allow hot pixels to be subtracted from science images, though not perfectly. Fortunately, the large majority (>80%) of new hot pixels can be repaired by warming (i.e. annealing) the CCDs to approximately room temperature. This is done monthly for both cameras and has proven successful in limiting the growth in the

Unfortunately, the other form of lattice damage from radiation damage, namely the creation of charge traps, does not respond to the annealing procedure. This damage appears to be cumulative and irreversible based upon both flight and ground test experience. These charge traps redistribute flux from one pixel to another during the readout process, and after several years of exposure to the space environment there are enough traps to make it a serious issue for observers to deal with. This is the subject of this White Paper.

Simply put, the charge traps degrade the efficiency with which charge is transferred from pixel to pixel during the readout of the CCD array. From the initial 0.999996 efficiency of the WFC3 CCDs at the time of launch, after 3 years they have an efficiency of about 0.9995 for charge packets with ~50 electrons. This implies that our “worst case” transfer across 2051 pixels would recover only about 36% of the initial charge collected in the pixel! In practice, things are not quite this bad. First, a significant fraction of the charge that fails to transfer from one pixel to the next (because it is held in a trap), is released by that trap within a couple of hundred milliseconds (a few pixel shifts). This is seen directly in the “charge trails” that follow hot pixels, cosmic rays, and bright stars. Hence, a measurement of the flux from a star within an aperture of several pixels radius will capture a sizable fraction of the charge that was originally in that star (see e.g. WFC3 ISR 2012-09 by Kai Noeske et al). But note that these trails extend, at very low percentages of the initial signal, to over 50 pixels in length (Figure 3).

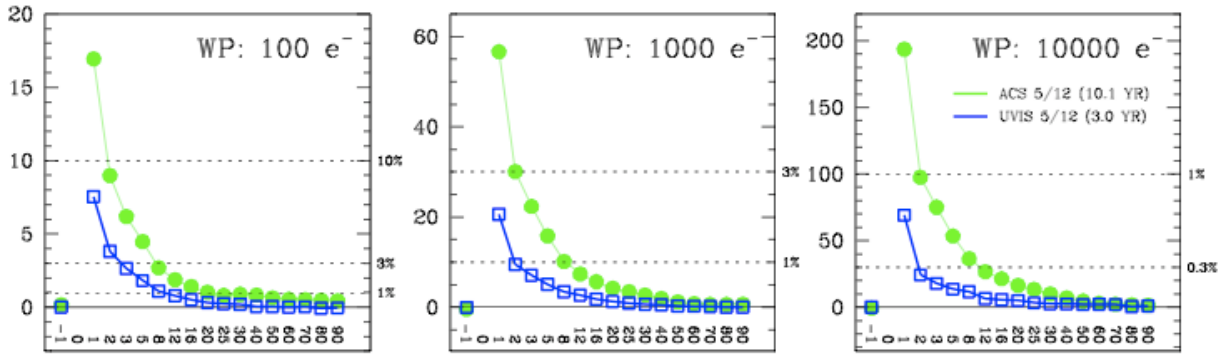


Figure 3: ACS (Green) and WFC3 (Blue) charge trails as of May 2012. The (nonlinear) X axis shows the distance from a "warm pixel" and the y axis shows the signal in electrons. Trails following warm pixels of 100, 1000, and 10,000 e⁻ are shown (courtesy of Jay Anderson).

Second, the charge traps can hold only a finite number of electrons within a pixel. Thus the presence of charge in the preceding charge packets (i.e. the pixels in the column between the pixel of interest and the transfer register) will fill some of those traps and make the transfer of charge significantly more efficient. While this improves the CTE, its value for each specific transfer, and thus the photometric calibration of every source in the image, depends upon both the morphology of the source and the distribution of electrons (from sources, cosmic rays, and hot pixels) in the detector column between the source and the transfer register. This poses an interesting calibration challenge!

When designing and analyzing HST CCD observations, users have several options to mitigate the impact of the declining CTE on their data. Unfortunately, none of these comes without a cost. From the discussion above, we may place these options into two classes: (1) efforts to increase the efficiency of the charge transfer during the CCD readout process, and (2) post-processing to either change the values of the pixels by de-convolving the effects of imperfect charge transfer or re-calibrate photometry after measurement to account for the anticipated losses. But before considering these options, we review the current state of the ACS and WFC3 CCD detectors.

2. Current State of the CCD Detectors

After 3 years of WFC3 and 10.3 years of ACS operation, radiation damage has had a cumulative and obvious effect on the performance of the CCD detectors. This is easily seen in the charge trails behind hot pixels and cosmic rays. Quantifying this effect, due to its complexities discussed above, is more challenging. A very simple measurement (EPER) is shown in Figure 4 (and is discussed in WFC3 ISR 2011-17 by V. Kozhurina-Platais et al.). This shows the decline over time (in days since installation in SM4) of the WFC3 CCD detectors CTE

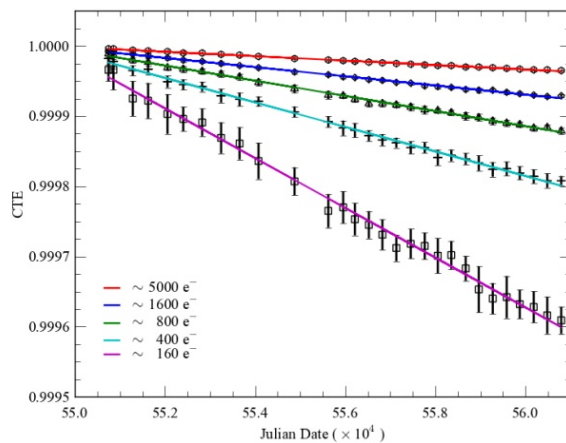


Figure 4: EPER trending for WFC3 CCDs. Losses are greater for smaller charge packets.

as a function of signal level.

A more revealing perspective on the impacts of CTE is shown in Figure 5. This comparison of warm pixels in short and long dark exposures illustrates the significant impact at low signal levels. The long darks were used to identify stable warm pixels and predict the number of counts they should receive in the short dark images. The observed number of electrons (as a function of distance from the transfer register) is shown. While these represent a worst case situation (zero background and single warm pixels –i.e. no shielding from the extended wings of a stellar PSF), they should be of concern to observers expecting to stack multiple images to observe very faint sources.

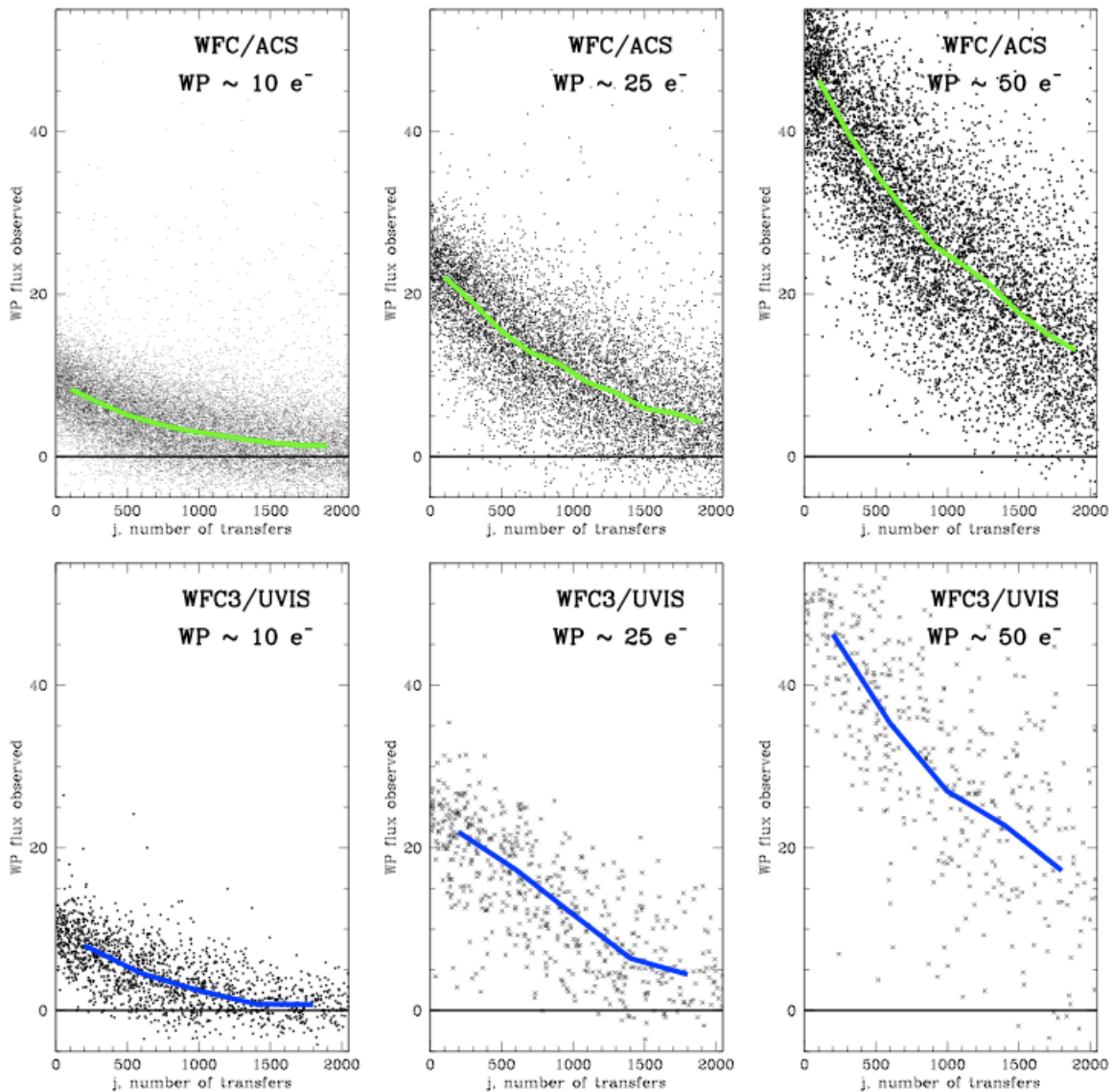


Figure 5: CTE Impact on Warm Pixels (courtesy Jay Anderson). These plots show the number of electrons received in a short-dark exposure (~ 100 s) as a function of the number of transfers for WPs that the long-dark exposures (~ 1000 s) predicted should have 10, 25, and 50 electrons. Note that for objects near the readout registers (very few transfers), the short-dark counts are what we would expect from pro-rating the long-dark. For both detectors, these data correspond to darks taken in May 2012.

3. Improving CTE

3.1 Optimizing Your Observing Strategy

The simplest mitigation of the imperfect CTE is to reduce the number of charge transfers required for a given source to reach the readout amplifier on the CCD. If the source of interest is small, placing it close to the corner of the detector will result in greatly enhanced net CTE. Naturally, this will benefit only a small subset of the planned observations but should be considered for observations of compact targets where the scientific interest in the surrounding field is limited or where multiple observations could be used to observe the area around the primary target and where inferior CTE for those surrounding observations is acceptable.

An alternate approach suitable for sparsely populated fields in which the sources of scientific interest are relatively bright (i.e. their worst-case CTE transfers still have sufficient S/N for the envisioned scientific analysis) is observations which are corrected directly for the CTE losses. This is calibrated for both instruments for point sources (see Noeske et al. WFC3 ISR 2012-09, Chiaberge et al. ACS ISR 2009-01). If observations may be obtained at multiple spacecraft roll angles (ideally at or near 90 degrees), then a significant fraction of the sources will have large variations in the number of pixel over which they must be transferred during readout – this permits a direct assessment of the reliability of the photometric calibrations. If observations are being taken on a field larger than the instantaneous field of view of the cameras, then stepping in the “Y” direction (i.e. along the CCD columns) with a small degree of overlap, will place some sources at both small and large distances from the transfer register (again permitting a direct assessment of the photometric reliability).

3.2 Increasing the Background

From the plots above, we see that the CTE is a strong function of the signal level in the pixels through which a charge packet must pass on its way to the transfer register. Unfortunately, this is not a simple linear function. A small packet of charge in a zero-background image will lose a larger fraction of its electrons in the transfer down the detector than will a larger packet of charge. If, however, this small packet of charge is preceded by other small packets of charge, then the preceding packets will end up filling most of the traps, so that our packet sees fewer empty traps, and more of its electrons will survive the transfer. Modest background levels (10-15

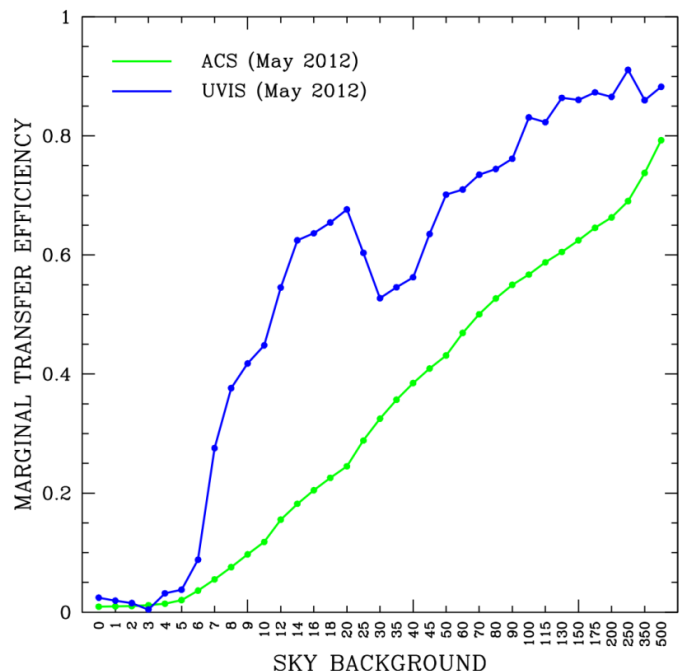


Figure 6: Improvement in CTE as a function of Background Level (Courtesy Jay Anderson). Plotted is the chance that an extra electron on top of a given background will survive from j=2048 to the readout register at j=0.

electrons in WFC3/UVIS and 50-100 electrons in ACS/WFC; see Figure 6) are able to keep many traps filled. Even on a moderate background, larger charge packets from brighter stars, hotter pixels, or cosmic rays (which typically deposit $\sim 10^3$ e-) will still experience some loss and trailing of their initial number of electrons. This is caused by the larger charge packet seeing a greater volume of the silicon lattice and thus being exposed to a greater number of traps. To improve the low signal level transfer capability of the WFC3 CCD's, the architecture of the devices has a structure to the potential ("a "mini-channel" or "notch") to enhance the transfer of small charge packets in the presence of charge traps. Recently obtained empirical data with WFC3 (see, e.g. Figure 6) shows a clearly non-linear impact to CTE as a function of the background signal level on the detector.

Conclusion: Observations with very low background (<10 e⁻ for WFC3 and <100 e⁻ for ACS) will suffer large losses for very faint sources. This is likely to be problematic for narrow band filters and observations in the UV where the background is very low. In some cases, the sources will effectively vanish during the readout transfers. In these cases, raising the background will greatly improve the CTE and thus the S/N of these sources. For users planning to stack or co-add multiple images to reach very faint limits, they should plan to achieve a background level of ~ 10 e⁻ for WFC3 and ~ 100 e⁻ for ACS. *N.B.* Even with the background increased, all sources will still suffer some CTE losses and it will still be necessary to provide photometric correction for the brighter sources.

The background can be increased in several ways: (1) longer exposure times, (2) the selection of a broader filter, (3) the selection of the other instrument, or (4) the addition of internally generated photons (i.e. "post-flash"). Items 1 and 2 are self-explanatory and Item 4 will be discussed in the next Section. For item 3, note that ACS has considerably higher response in the red combined with 60% greater pixel areas. Thus moderately long exposures in, for example, F606W may have sufficient background to mitigate much of the low light level CTE problem despite the far greater level of radiation damage.

3.3 Using Post-Flash to Increase the Background

ACS/WFC and WFC3/UVIS have nearly identical detector-housing assemblies. Both contain LED lamps configured to illuminate the side of the shutter blade that faces the CCD detector. Designed to provide fairly even illumination (20-30% variation) at low signal level, these lamps provide a "post-flash" capability. Our still rather limited (but supported by design analysis) experience with these lamps for WFC3/UVIS indicates that their illumination pattern and intensity is very repeatable ($\ll 1\%$ and $< 2\%$, respectively). Baggett et al (WFC3 ISR 2012-in preparation) provide a

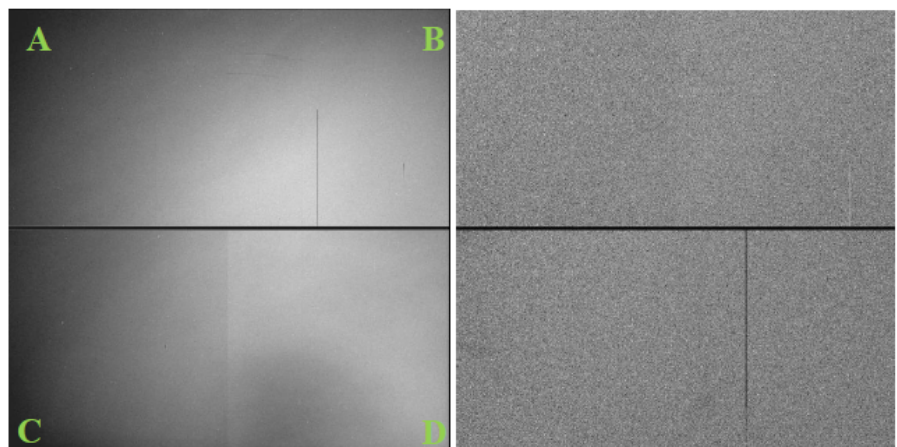


Figure 7: WFC3 Post-Flash lamp light distribution (left) and ratio of two images. (from Baggett, S. and Wheeler, T., WFC3 TIR 2012-01.

recent report discussing the inflight experience with the WFC3/UVIS post-flash lamp.

The post-flash lamp can be used to increase the background in an image. While doing something that adds noise to an image may seem counter-productive from a S/N perspective, it will significantly increase the efficiency of charge transfer for low-level sources when the background is otherwise very low. As a result, it can increase the signal much faster than it increases the noise.

WFC3/UVIS post-flash is a supported mode for Cycle 20. Although we are still in the process of calibrating and experimenting with the mode, it appears sufficiently promising and will be ready by late summer 2012. We anticipate that a post-flash capability for ACS/WFC will also be available in the same time frame. Internal ACS/WFC calibrations were taken on June 18 2012 (ID 12811) and are currently being analysed.

Observers should perform the following assessment of the potential benefits of adding a post-flash signal to their observations:

3.3.1 What is the natural background?

All observations have several sources of existing background: detector dark current, background illumination (mostly zodiacal light but sometimes a contribution from the bright earth limb), and light coming from the source(s) within the field of view.

The WFC3/UVIS detector dark current has steadily increased (as expected) since SM4 and is now around 6-7 electrons per pixel per hour. Thus for short exposures (e.g. less than 5-10 minutes), it does not contribute significantly to the background. The ACS/WFC detector dark current is now at 20-25 electrons per pixel per hour.

Motivated by the importance of the external backgrounds (zodi and earth) to the mitigation of the CTE problem, we have recently examined the full set of WFC3/UVIS observations to estimate the sky (see WFC3 ISR 2012-12, "WFC3/UVIS Sky Backgrounds" by S. Baggett and J.

Anderson). This report plots observed background signal as a function of exposure time for the UVIS filters (see Figures 9a,b) for examples in the F438W and F814W filters. Note the considerable scatter. A similar exercise has been carried out for all Cycle 18 ACS/WFC observations and the results are shown in Figures 9c,d for the F435W and F814W filters. Plots for all filters will be available shortly in an ISR (Sokol et al. 2012) or can be obtained via an email to help@stsci.edu.

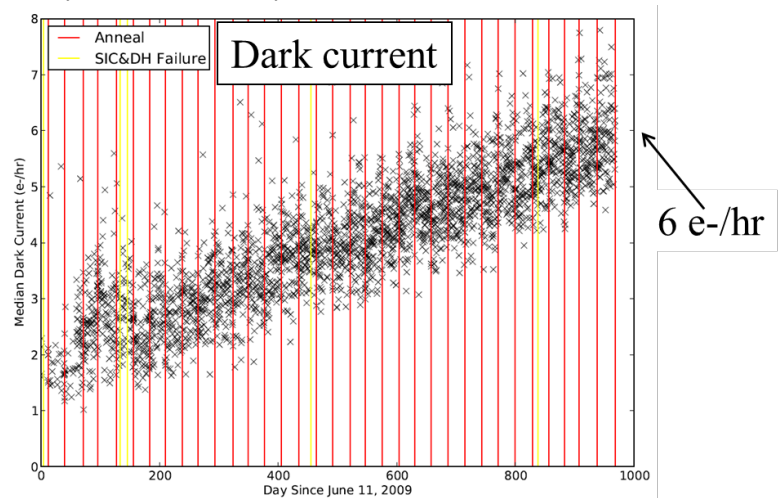


Figure 8: WFC3/UVIS Dark Current since SM4.

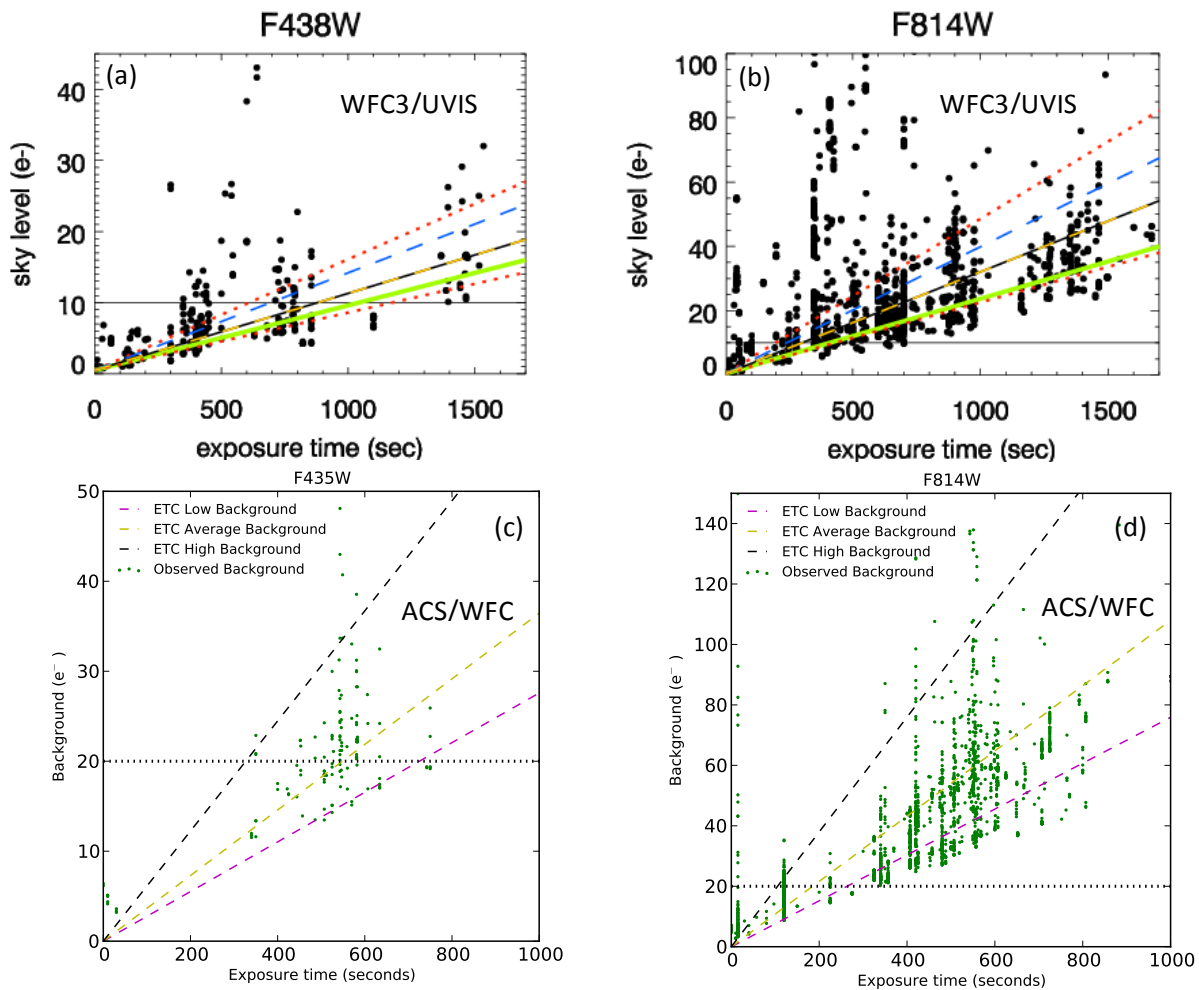


Figure 9: Measured background levels as a function of exposure time for the WFC3/UVIS F438W and F814W filters (top) and ACS/WFC F435W and F814W filters (bottom). For the top plots, the green line represents a manual fit to the lower boundary of the background level distribution. The other lines mark ETC values for various background levels. For both cameras, the ETC value for “low background” appears to represent the lower envelope of observed values reasonably well.

Some observations may be of sources that will clearly put sufficient signal into all or most pixels to mitigate the low signal level CTE problem. For example, observation of Jupiter, the cores of globular clusters or nearby galaxies in broad non-UV filters, etc.

3.3.2 How much additional signal is required to improve the CTE?

Our current experience (see again, Figure 6) indicates that 10-12 electrons are sufficient to restore most of the CTE for WFC3/UVIS observations of faint sources. ACS has been in space for over 10 years and consequently has far more charge traps. Even 100 electrons of background does not bring its CTE to the level reached by WFC3 with 10 electrons.

3.3.3 What are the costs of using a post-flash?

In this section, we discuss the use of post-flash for WFC3/UVIS only. Fortunately, the additional overhead times are generally very small (<10 seconds and sometimes zero). Furthermore, the post-flash lamp appears to be very stable and repeatable, so it should be possible to create high S/N images for

subtraction in the data processing pipeline. We are in the process of analyzing datasets obtained to explore the behavior of this lamp (see WFC3 Cal Program 12802). These datasets are available via MAST for users who wish to examine them.

The main consequence of post-flash is an increase in the background noise. In the worst case, a short exposure with zero background and dark current would require the addition of 10 electrons of post-flash. Thus the original readout noise of 3.1 electrons is effectively increased to 4.2 electrons. For a noise-limited observation, we would need to increase the exposure time by a factor of 1.84 to retain the same noise floor. In most cases, the impact is less severe. For example, a 1000 second exposure in F336W provides 4.5 electrons of background and dark current. Thus the original effective background + readout noise of 3.75 electrons, when increased to 4.2 electrons by the addition of ~5 electrons of post-flash, requires only a 25% increase in exposure time. Of course, the reason we are contemplating an increase in noise is that the preserved signal increases much faster than the noise.

3.4 Charge Injection (WFC3/UVIS only)

The WFC3/UVIS detector also has the ability to inject charge into rows continuously or with 1, 10, 17, or 25 row spacing (only 17 row spacing is supported at this time). The injected signal is ~15000 electrons (not adjustable) and results in about 18 electrons of additional noise in the injected rows. The adjacent rows (due to CTE effects) have between 3 and 7 electrons of effective noise. This capability has been supported since Cycle 19 but experience demonstrates that it is useful for very few types of observations. Its primary drawbacks are the uneven degree of protection from charge trapping in the rows between the injected charge rows, an increase in noise in the rows closest to the injected charge, and a very difficult calibration problem posed by the combination of sources in the field and the injected rows creating different levels of CTE at different places within the image.

Observers who wish to use this mode should consult the WFC3 Instrument Handbook and their Contact Scientist.

4. Post-Observation Image Restoration

Over the past year, the ACS team has developed and implemented a post-observation correction algorithm based upon the Anderson and Bedin (2010; PASP 122 1035) methodology. This empirical algorithm redistributes the counts in the image to undo the effects of the degraded CTE. Using the measured behavior of hot pixels, corrections as a function of flux were developed. While this algorithm does a good job of removing trails behind stars, cosmic rays, and hot pixels, it has one serious and fundamental limitation: it cannot restore the lost S/N in the image. This may be understood by thinking about a single hot pixel. Its charge with perfect CTE is all located within one pixel and therefore its noise is the combination of its shot noise and the noise due to readout and background in that one pixel. If it loses some of its counts due to imperfect CTE, then there will be fewer electrons in the hot-pixel itself, and more in the trailing pixels. In order to determine the original value of the hot pixel, the correction algorithm will determine how many counts the original hot pixel would have to have in order to be read-

out as the observed number, given the number of traps left full and empty by the preceding pixels. Since this is just a scaling-up of the observed value, the noise in the final reconstruction is related not to the original signal level, but the observed signal level. It is worth noting that read-noise can also introduce non-linear uncertainties in the reconstruction process, since it is added after the CTE-trailing has already happened.

Notwithstanding the above considerations, the reconstruction algorithm gives us our best understanding of what the original image was before transfer, and also helps us understand how the value of each pixel may have been modified by the transfer process. This algorithm is available in the ACS pipeline and standard calibrated products are now available both with and without this correction (see www.stsci.edu/hst/acs/performance/calacs_cte/calacs_cte.html for more details). The WFC3 team is now working to develop and calibrate a similar capability during the coming year.

An alternate method for post-observation restoration involves a simple recalibration of the photometry using correction curves that have been provided in Chiaberge et al (ACS ISR 2009-01) and Noeske et al (WFC3 ISR 2012-09). This can be effective for isolated point sources on flat backgrounds, but is less effective for extended sources or sources in crowded regions. One benefit of such an empirical recalibration is that it is less subject to readnoise amplification than the pixel-based reconstruction. These empirical corrections are also useful for planning observations: they allow an estimate of the CTE losses for point-like sources that can be expected in a near-future observation for a given background and source flux. The expected losses should be taken into consideration for a decision on the best CTE mitigation strategy, and if necessary, to adjust integration times to meet signal to noise requirements.

References and Useful Links

ACS:

ACS home page: <http://www.stsci.edu/hst/acs>

ACS pixel-based CTE correction documentation:

http://www.stsci.edu/hst/acs/performance/calacs_cte/calacs_cte.html

An Empirical Pixel-Based Correction for Imperfect CTE. I. HST's Advanced Camera for Surveys, Anderson & Bedin, 2010, PASP, 122, 1035 <http://adsabs.harvard.edu/abs/2010PASP..122.1035A>

Updated CTE photometric correction for WFC and HRC: Chiaberge et al. ACS ISR 2009-01

<http://www.stsci.edu/hst/acs/documents/isrs/isr0901.pdf>

ACS/WFC Sky Backgrounds ISR: Sokol et al. ACS ISR 2012-04, in prep. For information and plots of sky background for each filter, contact help@stsci.edu

ACS post-flash internal calibration program: ID 12811

<http://www.stsci.edu/cgi-bin/get-proposal-info?id=12811&submit=Go&observatory=HST>

WFC3:

WFC3 home page: <http://www.stsci.edu/hst/wfc3>

WFC3/UVIS Sky Backgrounds ISR: Baggett & Anderson, WFC3 ISR 2012-12

<http://www.stsci.edu/hst/wfc3/documents/ISRs/WFC3-2012-12.pdf>

WFC3 UVIS Charge Transfer Efficiency October 2009 to October 2011: Noeske et al. WFC3 ISR 2012-09

<http://www.stsci.edu/hst/wfc3/documents/ISRs/WFC3-2012-09.pdf>

WFC3/UVIS CTE-EPER Measurement: Cycle 17 & 18: Kozhurina-Platais et al. WFC3 ISR 2011-17

<http://www.stsci.edu/hst/wfc3/documents/ISRs/WFC3-2011-17.pdf>

WFC3 post-flash internal calibration program: ID 12802

<http://www.stsci.edu/cgi-bin/get-proposal-info?id=12802&submit=Go&observatory=HST>

WFC3/UVIS TV3 Post-flash Results: Baggett & Wheeler WFC3 TIR 2012-01

<http://www.stsci.edu/hst/wfc3/documents/TIRs/WFC3-TIR-2012-01.pdf>