Minimizing CTE losses in the WFC3 CCDs: Post Flash vs. Charge Injection

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ABSTRACT
We present a comparative study of the relative merits of Post Flash and Charge Injection in mitigating the loss of charge transfer efficiency in the CCDs to be flown on Wide Field Camera 3. The study is based on the observed photometry of the $^{55}$Fe X-ray emission, whose photons are recorded on the CCD as individual sources of apparent flux equal to 1,620 e$^-$, equivalent to that from a source with V~26 in ~1/2 hour exposure, and thus our conclusions directly apply to relatively faint observations. Extrapolations to fainter observations are also discussed, based on observations made with WFPC2 and analyzed by Whitmore et al. The primary parameters considered in the comparison are sensitivity and photometric accuracy. We found that the current implementation of Charge Injection for the WFC3 detectors is generally superior to Post Flash in that it allows to obtain generally superior remedial action against the degradation of photometric accuracy and sensitivity induced by losses of charge transfer efficiency while avoiding the high Poisson noise characteristic of Post Flash correction.

Introduction
Charge-Coupled Device (CCD) detectors work by recording the amount of electric charge deposited in the detector’s pixels by impinging electromagnetic radiation. To be recorded, a packet of charge first needs to be physically moved, or "transferred", from the location on the detector’s surface where it has been generated to the serial register, where it can be read by the read-out amplifier. This is accomplished by shifting the charge along rows or
columns to adjacent pixels in a step-by-step sequence until it reaches the serial register pixels in those rows or columns. Since the amount of charge of a packet is proportional to the electromagnetic flux that has generated it, the capability of a CCD to perform charge transfer operations in a way that minimally affects the charge content of the packet is crucial in astronomical applications. Unfortunately, in the case of CCDs used in instruments installed in space-based observatories, including HST, Charge Transfer Efficiency (CTE) is degraded by the cumulative damage made to the detector’s silicon lattice by the intense cosmic radiation encountered in the orbital environment. Already after ~months of exposure the performance of detectors begins to suffer, and after ~years they become severely compromised, and significant loss of sensitivity and photometric accuracy are observed.

A number of remedial actions can be adopted to mitigate the effects of CTE degradation. This Instrument Science Report documents a comparative study of two of them, Pre/Post Flash (PF) and Charge Injection (CI), made using a CCD similar to the flight device that will equip the Ultraviolet and ViSual (UVIS) channel of Wide Field Camera 3 (WFC3). CTE degradation in CCDs used in HST instruments and the impact on the sensitivity and photometric performance of the instruments has been discussed, for example, by Whitmore & Heyer (2002), Stiavelli et al. (2001), Riess (1999, 2000,); see also the STScI Charge Transfer Efficiency working group at http://www.stsci.edu/hst/acs/performance/cte_workgroup/cte_workgroup.html. Cawley & Hanely (2000, 2001) and Hanley & Cawley (2001) discussed techniques commonly used to simulate the damage by cosmic radiation in CCDs and to measure CTE degradation. Stiavelli, Hill & Polidan (2001) reviewed the technique of charge injection as implemented for WFC3 and characterized its performance in initial implementations of the WFC3 hardware (CCD and electronics). This work presents a comparative study of the performance of the current implementations of PF and CI for WFC3 CCDs in remeding CTE degradation. In particular, we focus on the photometric performance, quantified by sensitivity and photometric accuracy, of a damaged CCD treated with the two techniques with the goal of identifying the optimal one.

**Charge Transfer Efficiency**

The Charge Transfer Efficiency of a CCD is its capability to move the charge contained in one of its pixels to an adjacent one without varying the amount of charge. It is measured as the fraction of charge that is successfully transferred to adjacent pixels, and in good science-quality detectors it is of the order of ~0.999995 or better. Charge is lost because during transfer operations, defects in the silicon lattice, or "traps", can remove some amount of charge from the transiting packet and retain it. These charge losses happen multiple times during the journey of the packet from its original location to the serial register, depending
on the density of traps. When the remainder of the initial packet finally reaches the serial register, the amount of charge measured by the amplifier and recorded is less than the original value generated by the photons. The charge deficit is proportional to the charge transfer inefficiency of the CCD (the average amount of charge removed by traps during each transfer operation, namely 1-CTE) and the distance that the packet has traveled. In large-format detectors, such as those of ACS/WFC and WFC3/UVIS, the distance that some packets have to travel is large, and the net losses can be high. Schematically, when an "active" trap captures charge, it retains it for some time and becomes "passive", namely does not continue to subtract charge from other transiting packets. The charge is not kept by the trap indefinitely, however, but it is released after some time in a gradual fashion during subsequent transfer operations (i.e. the charge "trails" backward from the trap along the row or column where the transfer operation is being conducted). The trap then becomes active again. The released charge can add to other charge packets that are traveling behind towards the trap. It can also become trapped in other traps and follow similar vicissitudes. Thus, all the traps involved effectively also act as sources of progressively fainter amount of charge and induce random fluctuations of charge in transiting packets. This translates into an increase of photometric scatter.

CTE degrades as a result of damage to the silicon lattice done by cosmic radiation, and this damage is cumulative with time. With sufficient time, CTE degrades to a point where the effects can even be seen by eye. This is illustrated in Figure 1, where the gradual release of charge subtracted from sources by the traps is observed as trails that follow the sources. In this image and in following ones the pixels of the serial register are horizontally below line 1, and hence the charge is moved vertically downward along columns.
Figure 1. $^{55}$Fe sources recorded with CCD 43-152 damaged by a 5-year equivalent dosage of irradiation. The effects of degraded CTE are clearly observed visually as charge trailing after the sources. The pixels of the serial register are displaced horizontally at the bottom of the CCD, therefore charge is moved vertically along columns from top to bottom.

Finally, it is important to note that there are also losses of CTE along the serial register, although these are generally much smaller than those in the body of the detector.

Even from this very schematic description of the problem, it is clear that good CTE is critical to the scientific performance of CCDs. If left uncorrected, the primary effect of degraded CTE is a systematic bias in the photometric performance of the detector such that sources appear to be systematically fainter the further away they are located from the serial register. Since a net amount of charge is removed from sources, it also causes loss of sensitivity. Equally insidious, because of the random nature of the phenomenon, it is the increase of the photometric scatter, which degrades the photometric accuracy.
Characterizing the CTE losses of WFC3’s CCDs

Degradation of CTE is measured in the laboratory on detectors exposed to dosages of radiation calibrated to simulate permanence in the space environment of selected length of time. The damaged detector is subsequently used to obtain images of artificial sources of known luminosity, and the recovered photometry is then studied as a function of spatial position of the source on the CCD, such as the distance from the serial register. Artificial sources are provided by soft X-ray photons from narrow emission lines of radioactive isotopes as, such as $^{55}$Fe. The individual photons of one of such lines of $^{55}$Fe are detected by CCD as individual sources with average apparent flux equal to 1,620 $e^-$, and thus provide ideal artificial sources that can be studied with techniques similar to those commonly adopted in the astronomical practice (Cawley & Hanley 2000, 2001).

We have studied CTE degradation on Marconi’s CCDs of the same type as those that will be flown on the UVIS channel of Wide Field Camera 3 (WFC3), specifically part 43-152. We have not considered CTE losses along the serial register, but only those in the CCD. Frames exposed to the $^{55}$Fe photons have been taken at the GSFC Detector Characterization Lab (see Stiavelli et al. 2001) with the CCD before it was subject to radiation damage, and after it has been exposed to radiation dosages equivalent to 2.5- and 5-year period in space, respectively. The image reproduced in Figure 1 shows a portion of a frame taken with CCD 43-152 after 5-years equivalent dosage. We have obtained images of 4-sec exposure time, which provide enough events (or "hits" in what follows) for good statistics, and at the same time avoid too high a surface density of sources. Such a situation would bias CTE measures because closely spaced sources effectively act as sources of a background of charge that mitigates CTE losses suffered from any given source. As the figure shows, the hits have essentially the same morphology as cosmic-ray events commonly encountered during astronomical observations.

We have carried out photometry of the hits using SExtractor (Bertin & Arnouts 1996), a popular software package for faint galaxy photometry. The software automatically detects the hits and measures their apparent flux, and its main advantage over other popular packages, such as DAOPHOT or DPHOT, is that it is also capable to measure isophotal magnitudes, while the latter only produce aperture magnitudes within circular apertures. Isophotal magnitudes are required in this case, because the $^{55}$Fe photons hit the CCD with a range of angles of incidence, and thus have morphology ranging from circular to elongated strips.
We have quantified the effects of degradation of CTE by studying the observed flux of the hits as a function of their distance from the serial register, namely their y-coordinate in the CCD reference frame. More specifically, we have studied the distribution of the flux of the hits in horizontal bins of 25 pixel size, identified both the mode of this distribution (which corresponds to the original value of 1.620 e⁻) in each bin and its average (which is slightly lower than the average, because the distribution is not symmetric), and plotted them as a function of the y-coordinate of the bin. This is shown in the upper and lower left panel of Figure 2.

Figure 2. The effects of CTE losses. The two left panels show the mode (top) and average (bottom) value of the recovered flux of the ⁵⁵Fe hits within horizontal bins of width Δy=25 pixels as a function of the distance to the serial register (y coordinate). Black points represent the pre-irradiation CCD (i.e. no CTE losses), red points to the 2.5-year irradiated case, and magenta points to the 5-year irradiated one. The broken horizontal lines one the left panels show the expected flux value of 1.620 e⁻. Note that the mode is an unbiased estimator of the true value of the flux in the bins, while the average is biased towards lower values because of the asymmetrical distribution. The right panels show the distribution of S/N (top) and photometric accuracy.
(bottom), namely the ratio of the $1-\sigma$ dispersion of the flux to the average within a bin as a function of the bin distance from the serial register. The broken horizontal lines are the theoretical Poisson value of S/N and photometric accuracy for sources with 1,620 e$^-$ apparent flux, respectively. CTE losses are observed as gradients of charge loss as a function of distance to the serial register (left panels), as a decrease of sensitivity (upper right panel), and as a decrease in photometric accuracy, i.e. an increased in scatter (bottom right panel). About 15% and 25% of the charge is lost in the 2.5- and 5-year damaged detector, respectively, from hits detected at the top of the CCD. Finally, note that fluctuations of gain in the experimental setup are observed as variations of the observed flux of the hits at zero distance from the serial register.

Figure 2 for the mode and the average, respectively, where black points are relative to the non-damaged detector, i.e. they show no CTE losses, the red points to the detector irradiated to the 2.5-year equivalent dosage, and the magenta points to the 5-year equivalent dosage. In each case, straight lines represent the linear fit to the data points, while the horizontal broken lines make the 1,620 e$^-$ value. The degradation of the CTE results in a space-dependent systematic photometric bias, which is observed as an apparent dimming of the intensity of the line as a function of the y-coordinate (in this study we have neglected the much smaller CTE degradation along the x-coordinate). Note that the figure shows slight variations of gain in the experimental setup, visible as fluctuations of the amount of flux in the bin placed just above the serial register.

Edge-to-edge variations across the CCD of apparent flux of identical sources at the 2.5-year time is ~14%; at the 5-year time is ~21%. The CTE degradation occurs more quickly, by about a factor of ~2, during the first 1/2 of the 5-year period of radiation damage than during the second half, and the amount of charge lost scales linearly with the distance to the serial register.

If the effect of CTE degradation were only a space-dependent bias in the photometry, this could have been easily calibrated. Unfortunately, once traps have developed in the CCD, charge is transferred from one pixel to the next in a stochastic fashion. The charge subtracted to a packet and retained in a trap is released at random during subsequent transfer operations, adding to the charge of another transient packet, with the result that packets not only can lose charge in a random way, but they can also gain it. This increases the scatter in the photometry, as it is illustrated in the lower right panel of Figure 2, which plots the ratio of the $1-\sigma$ scatter of the photometry of the hits within each bin to the mean of the distribution. As done before, the color coding is such that black circles denote the undamaged CCD, red circles the 2.5-year damaged CCD, and the magenta circles the 5-year one. CTE degradation increases the photometric scatter by up to a factor of 2, and prevents one from achieving photometric uniformity better than ~3.5 percent (the dashed horizontal line is the theoretical value from Poisson statistics for the case of sources with flux equal to 1,620 e$^-$). Note that, as expected, the scatter is higher for the hits that are more distant from the serial register, since they suffered more interactions with traps. Also, note
that in the case of the 5-year damaged CCD the scatter is only marginally higher than that the 2.5-year one.

Finally, the effects of CTE on the S/N ratio as a function of the y-coordinate are plotted in the upper right panel of Figure 2 with the same color coding adopted above. At its worst, the S/N is degraded by as much 40%, going from ~37 in the case of the undamaged detector to ~22 for the hits recorded withy the 5-year damaged detector and located at large distant from the serial register. Although significant, such a loss of sensitivity is still not crucial for sources in this particular flux range. At fainter levels, however, it can make the difference between a detection and a miss.

**Remedying CTE Degradation: Charge Injection vs. Pre/Post Flash**

Remedies of the degradation of CTE are based on the fact that if the traps of a damaged CCD are kept filled with charge, it is less likely that they trap additional charge from transiting packets moved through them during charge transfer operations (Janesick 2001). Two methods of providing traps with charge have been considered for the CCDs of WFC3, namely charge injection (CI) and pre/post flash (PF).

In the case of CI, charge is electronically deposited into the pixels of the detector, before or after an exposure, either in all pixel or only in selected locations. The first case offers the best results if if frame-to-frame variations of charge injected in a given pixel can be kept small so that a calibration image can be made and subtracted from the science data without adding too much additional noise. For the second case we studied a configuration where the charge is injected in single-pixel rows separated by a given number of pixels $\Delta y$. When the CCD is read out, the injected line "sweeps" through traps and fills them with charge making them "passive", i.e incapable of trapping additional charge from passing sources. However, a trap can retains the charge only for a limited number of discrete charge transfer operations and then it releases most of it, becoming active again (see Stiavelli, Hill & Polidan 2001). If the spacing between the charge injected lines is small enough that the traps remain filled with enough charge for most of the charge transfer operations before the arrival of the next charge-injected line, the technique provides an effective method of mitigating CTE degradation. This method is practical even in presence of relatively large instabilities in the amount of charge injected in the lines, as long as enough charge is available. In this case, subtraction of the pattern of injected charge from the image through calibration frames is not effective, and area corresponding to the injected lines is lost to the observations, although its value is small, typically less than ~10%.
In the case of PF, charge is deposited in each pixel by photons emitted by an appropriate source of light (e.g. a lamp), either before an exposure is taken (pre-flash) or after it (post-flash). The average amount of charge per pixel is easily controlled through the exposure time to the light source and through the intensity of the light, and the fluctuations of charge in each pixel follow the photon (Poisson) statistics.

Thus, the difference between PF and CI comes down to the noise properties of the amount of charge deposited in the detector’s pixels, poisson in the first case and controlled by the accuracy of the electronics parameters in the second. If the total amount of charge required to reduce CTE losses to a desired level is relatively small so that the poisson noise is also small, PF is a desirable solution because of its design simplicity. On the other hand, if the required charge is large and/or if the electronics is stable enough that charge can be injected into the detector with great accuracy (i.e. the noise added to the image is small), then CI is a better alternative.

**Post Flash**

Figure 3 and 4 show the effects of post flash in mitigating CTE losses in the 2.5- and 5-year irradiated device, respectively. Figures 3a and 4a show the effects of a low-level post flash illumination of 100 (cyan points) and 200 (green points) e\(^-\), respectively, while Figures 3b and 4b do the same for higher levels, namely 500 (blue points), 1000 (cyan points) and 2000 (green points) e\(^-\), respectively. For both levels of radiation damage, low-level PF approximately halves the gradient of charge lossing across the CCD due to CTE inefficiency, while higher levels achieve a superior correction, restoring up to ~80% of the damage. PF is also effective in mitigating the degradation of photometric accuracy. However, low-level pre-flash can only achieve modest mitigation to the loss of sensitivity while high-level one actually decreases sensitivity further, because of the added Poisson noise. Note, to this purpose, that the case illustrated in the Figures is an optimistic one, because we used isophotal magnitudes for the hits. When working with galaxies or stars of comparable magnitudes, the apertures will be larger (whether isophotal or fixed to match the PSF), reducing the sensitivity even further (more on this later).
Figure 3a. The effects of low level PF in mitigating CTE losses in the 2.5-year irradiated CCD. Cyan points represent 100 e\(^-\) PF, green points 200 e\(^-\) PF. Other symbols are as in Figure 2.
Figure 3b. As Figure 3a, but for 500 (blue points), 1,000 (green points) and 2,000 (cyan points) $e^-$ of PF level. Other symbols are as Figure 2.
Figure 4a. The effects of low level PF in mitigating CTE losses in the 5-year irradiated CCD. Cyan points represent a PF level of 100 e⁻, green points of 200 e⁻. Other symbols are as in Figure 2.
Figure 4b. As Figure 3a, but for 500 (blue points), 1,000 (green points) and 2,000 (cyan points) e\(^-\) of PF level. Other symbols are as Figure 2

**Charge Injection**

We will now discuss the results obtained with CI, both in its discrete implementation, namely charge injected in horizontal lines 1-pixel wide space by a given amount, and continuous implementation, namely uniformly over the whole CCD. Figure 5 and 6 show the effect of discrete charge injection on the 2.5- and 5-year irradiated device, respectively. Figures 5a shows the case of charge injected every 25 lines (blue points) and 50 lines (cyan points), respectively, while Figure 5b shows the case of 100 lines (blue points) and 200 lines (cyan points), respectively. In all cases 10,000 e\(^-\) have been injected. Note that more closely spaced injection achieve better results. Note also the bottom-right panel,
which shows the average dispersion at a given pixel pixel within the bin plotted as a function of the distance from the nearest low injected line. For the 25- and 50-line case the dispersion decreases as the distance increases, i.e. as the amount of individual charge-transfer operations decreases, before the next charge-injected line (i.e. the top line) sweeps through that particular position. The effect is not observed in the 100- and 200-line cases.

**Figure 5a.** The effects of discrete CI in mitigating CTE losses on the 2.5-year irradiated CCD. Blue points are the case of 10,000 e- injected in 1-pixel wide horizontal lines separated by 25 pixels; cyan points the case of lines separated by 50 pixels. Panels are similar to those of Figure 2, except the bottom right one, which shows the average dispersion of flux of hits within their bin as a function of the distance to the nearest low line with injected charge. The dispersion is high for pixels right above the injected line because they have to wait until the arrival of the upper injected line (i.e. the full bin width) before they get charge to make nearby traps passive. The dispersion is low for hits just below the injected line because they get its charge after a few charge transfer operations.
Figure 5b. As Figure 5a, but now blue points represent lines spaced by 100 pixels and cyan points line spaced 200 pixels. These separations are likely too large to provide an effective remedy against CTE losses and the dispersion (bottom right panel) does not show the same trend observed in Figure 5a.

Figures 6a and 6b are relative to the 5-year irradiated device, and in this case only the 25- and 50-line spacing, respectively, are shown. Here, however, we show the effects of varying the amount of injected charge per pixel, where blue, green and cyan dots represent 10,000, 15,000 and 20,000 electrons, respectively. There is only a modest dependence with the total amount of charge injected of the ability of discrete charge injection in mitigating CTE losses. Also, discrete charge injection apparently loses strength in its “curative” capabilities in the 5-year damaged device, as evidenced by the steep gradients of charge loss observed across the detector, the relatively large photometric scatter and low S/N.
Figure 6a. As for Figure 5a, but relative to the 5-year irradiated CCD and for injected lines separated by 25 pixels only. In this case blue, cyan and green points represent level of injected charge of 10,000, 15,000, and 20,000 e\(^-\), respectively. Notice that the effect of mitigation of CTE losses is essentially independent on the amount of charge injected.
Figure 6b. As in figure 6a, but with injected lines spaced by 50 pixels. As in the previous case, the mitigation of CTE losses is independent, in this case, from the amount of charge injected in the lines. Note that in this case, where lines are separated by a larger distance than in the previous case, the remedial capabilities of the technique against CTE losses are diminished.

Continuous CI for WFC3 can currently be achieved with very good uniformity and relatively low noise level. Figure 7 shows the pattern of injected charge on the 5-year damaged detector, in which on average 10,000 electrons are deposited in each pixel. The pattern is very stable and can be repeated with accuracy, with a frame-to-frame noise (in a given pixel) of 15 e⁻ rms. This is significantly lower than the noise measured in earlier implementations of CI (Stiavelli, Hill & Polidan 2001). A calibration frame can, therefore, be easily made and subtracted from injected frames, quadratically adding to its noise level a contribution of 15 e⁻ rms. Figures 8 shows a “science” frame obtained with the 5-year irradiated device and treated with continuous CI from which the injection frame has been subtracted, while Figure 9 plots the corresponding pixel histogram, demonstrating the
good noise characteristics. Note that no charge trailing due to CTE losses can be visually detected. Finally, Figure 10 shows the efficacy of the technique. The mitigation of CTE losses is excellent, with only a minimal gradient of charge loss left and correspondingly minimal degradation of sensitivity and photometric accuracy, due to the effective read-out noise, which is now 15 e⁻ rms instead of the nominal 5 e⁻ rms. It is quite possible that further improvement to the electronics will result in a lower noise for continuous charge injection, possibly as low as 7-10 e⁻ rms.

**Figure 7.** The pattern of continuously injected charge in the 5-year irradiated CCD. Approximately 10,000 e⁻ per pixel have been injected. The pattern is very stable and reproducible, and calibration frames are easily made for subtraction from science frames with CI.
Figure 8. An image of the 55Fe “sources” taken with the 5-year irradiated CCD, treated with continuous CI from which a master charge-injection calibration frame has been subtracted. The injected charge is removed very effectively and with great regularity, leaving a residual noise of 15 e- rms (see Figure 9). Note that no trailing of charge can be observed (compare against Figure 1, taken in similar conditions), indicating that CTE losses are being very effectively mitigated.
Figure 9. The pixel value distribution of the images shown in Figure 8. The values of background pixels follow a Gaussian distribution with good approximation, with $\sigma=15$ e-. Pixel values relative to sources are observed as a high-end tail.
Figure 10. The ability of continuous CI in remedi CTE losses (cyan points). Other symbols are as in Figure 2. The gradient of charge loss is nearly eliminated, and sensitivity and photometric accuracy degradation is correspondingly very limited.

Figure 11 shows a direct comparison between continuous CI (red points) and a PF of 2,000 e\(^{-}\) (blue points). For the latter case, this time we considered both isophotal apertures (filled points) and fixed, circular ones with 5 pixel diameter (open points in the red panels). It is seen that while a PF of 2,000 e\(^{-}\) achieves almost (but not quite) the same remedial capabilities of 10,000 e\(^{-}\) of continuous CI in mitigating CTE losses, the effect of the much higher Poisson noise (45 vs. 15 e\(^{-}\) rms) are clearly observed in the sensitivity and photometric accuracy. Note also the dramatic loss of sensitivity and decrease in photometric accuracy when using larger apertures. A qualitatively similar effect is also present in the
case of charge injection (not shown in the picture), but its magnitude is at least ~3 times smaller (for very faint sources) or smaller, depending on the filter used in the observations.

Finally, it is important to note that while increasing the effective read-out noise from ~5 to 15 e⁻ rms has relatively small consequences for bright objects and/or for observations where the sky background is relatively large, e.g. long exposure with the F606W filter, its effects become progressively more severe at shorter wavelengths, for fainter objects and/or with narrower filters. For example, for a flat spectrum (in $f_{\nu}$ units) source with $V$~28 observed through the F606W filter (~220 e⁻ in 1800 sec exposure) the above increase in noise corresponds to a decrease in sensitivity of $\Delta m$~0.3. For a source with the same spectrum, $V$~24, observed through the F275W filter, the decrease in sensitivity is $\Delta m$~1 mag (S/N drops from 5.8 to 2.1). Clearly, a reduction of the residual noise associated to continuous charge injection is highly desirable and will make the technique unique in mitigating CTE losses.
Figure 11. Comparison between continuous CI (red points) and 2000 e- level PF (blue points). Open symbols in the right panel represent photometry obtained with fixed circular aperture of 5 pixel diameter, while the filled symbols represent isophotometry, as done in all the previous figures. The larger aperture is similar to that required to encompass 88% of the light of the optical PSF of UVIS, and it illustrates the dramatic effect of the Poisson noise associated to the level of PF required to achieve CTE loss mitigation comparable to that of CI, namely 44 e- rms vs. 15 e- rms. Using fixed aperture in the case of CI would also produce a qualitatively similar effect, but its magnitude is about a factor of ~3 smaller. Note that even 2,000 e- of PF level do not achieve the same remedial capability of CI.

The Faint Objects Limit

The results discussed so far are only valid to sources with observed flux similar to that of $^{55}$Fe photons, namely 1,620 e-, which corresponds to a flat-spectrum source with $V \sim 25.8$.
observed through the F606W filter in a 1,800 sec exposure, therefore a moderately faint source (for HST standards). However, while no empirical information is available on the behaviour of the proposed remedial actions against CTE degradation at fainter flux levels, as well as information on the effects of CTE losses on fainter sources, some insight can be gained from observations taken with WFPC2 and analyzed by Whitmore et al. 2002. Table 1 (Whitmore, private communication) lists the average fractional flux loss suffered by stellar sources in a given flux range (tabulated in DN) recorded with the WFC CCDs of WFPC2 through the F336W filter with and without post flash treatment. The last row of the table lists the loss of sensitivity as a function of the level of Post Flash and shows that faint sources are proportionally more affected by CTE losses than bright one.

<table>
<thead>
<tr>
<th>Flux (DN)</th>
<th>no Post Flash</th>
<th>25 e(^{-}) Post Flash</th>
<th>250 e(^{-}) Post Flash</th>
<th>1,700 e(^{-}) Post Flash</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-50</td>
<td>37.7 +/- 4.7%</td>
<td>11.8 +/- 2.4%</td>
<td>3.9 +/- 5.3%</td>
<td>not enough stars</td>
</tr>
<tr>
<td>50-200</td>
<td>23.3 +/- 2.1%</td>
<td>8.3 +/- 1.4%</td>
<td>3.3 +/- 2.0%</td>
<td>5.8 +/- 3.4%</td>
</tr>
<tr>
<td>200-500</td>
<td>16.6 +/- 4.0%</td>
<td>8.7 +/- 1.8%</td>
<td>5.5 +/- 2.2%</td>
<td>-1.8 +/- 2.8%</td>
</tr>
<tr>
<td>500-2,000</td>
<td>8.8 +/- 5.6%</td>
<td>10.2 +/- 4.3%</td>
<td>-1.2 +/- 4.2%</td>
<td>2.3 +/- 1.6%</td>
</tr>
<tr>
<td>(\Delta m)</td>
<td>~0.0</td>
<td>~0.4</td>
<td>~0.9</td>
<td>~1.5</td>
</tr>
</tbody>
</table>

It can be seen that the application of a low amount of post flash (e.g. 25 e\(^{-}\)) is very effective in reducing the differential loss for sources of different flux at the cost of a relatively modest loss of sensitivity (note that with a gain of 7, a flux in the range 20-50 DN corresponds to 140-350 e\(^{-}\), similar to the V\(~26\) source considered before). If a similar behaviour is valid for WFC3’s CCDs, this suggests that low-level pre flash could, in principle, be used for observations of faint sources with low background (B-band and shorter wavelengths). For example, let’s consider the case of a source with apparent flux equal to 200 e\(^{-}\) observed in conditions of very low background (e.g., in the UV). Figure 4a shows that S/N losses in the 5-year irradiated CCD for sources with flux equal to 1,620 e\(^{-}\) are of the order of 32\%, while Table 1 suggests that with low level PF, CTE losses become independent of the source flux. Assuming that this is indeed the case, we conclude that our source, which would be detected with S/N\(~8\) in the undamaged CCD, is now detected with S/N\(~5.5\). On the other hand, if treated with CI, the source does not do as well, because even if now we can neglect CTE losses, the added noise of 15 e\(^{-}\) rms lowers the sensitivity to S/N\(~2.6\), below the typical detection threshold. If the CI noise were 7 e\(^{-}\), then the sensitivity would be S/N\(~5.3\), comparable to the PF case considered. Of course, CI is still to be preferred every time the background level is comparable or higher than the added noise contribution, regardless of the source brightness (for example, ~1/2 orbit integration with the
F606W filter). Also note that a low-level sky background effectively acts as a low-level PF.

**Conclusions**

Charge injection can have great remedial capability against CTE losses. The present implementation of the technique with the WFC3 hardware (electronics and CCD) achieves a residual noise of 15 e⁻ rms, which makes it superior to post/pre flash in almost all observations, except perhaps very faint observations (e.g. V>28) with low background (passbands bluer than the V band or narrow-band filters). In this cases a low level pre/post flash might be helpful in mitigating the effects of CTE losses. Further reduction of the noise level of CI, which can possibly be reduced to 7-10 e⁻, will make the technique truly unique to contain the annoying effect of cosmic radiation damage on CCD operated in the space environment.

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