SPACE TELESCOPE SCIENCE INSTITUTE
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Instrument Science Report WFPC2 2010-001

WFPC2 Standard Star CTE

M. McMaster and J. Biretta
June 24, 2010

ABSTRACT

Observations of the WFPC2 standard star GRW+70D5824 were made at five positions along the diagonal of each detector to directly evaluate CTE effects on standard star data. Two filters commonly used for standard star monitoring, F170W and F555W, were tested. The data were subsequently corrected with the Dolphin CTE equations, and the results were studied for any residual variations in photometry with detector position. Two (and sometimes three) exposures were made at each detector position. In the course of our work we discovered a significant 'first exposure effect' where the first exposure produced significantly fewer counts than the subsequent ones. For both filters, the count deficit in the first exposures increased approximately linearly with Y position, and reached ~5% at Y=800. For the F555W filter, the Dolphin equations were reasonably accurate, and the first exposures tend to be under corrected by about 0.5%, and the second exposures were over-corrected by about 1.5%, both evaluated at the chip centers. For F170W the residual errors are larger, with the first exposures being ~3% over-corrected, and the second exposures being 6% to 7% over-corrected, both at the chip centers. These results for F170W suggest systematic errors of 3% to 7% could be present in the photometric calibration of UV filters for data taken late in the WFPC2 mission.

Introduction

The star, GRW+70D5824, served as the primary photometric standard for WFPC2 throughout its more than 15 year mission and was used in monthly observations to calibrate the camera's photometric throughput, and monitor both long- and short-term throughput variations. CCD detectors, such as those used in WFPC2 are subject to problems with charge transfer efficiency (CTE). During readout of the detector, some of the charge comprising the latent image of the target can be trapped in the detector silicon, causing the image to appear too faint. The size of this effect depends on many factors, including the distance of the target on the chip to the readout amplifier (i.e., number of vertical transfers or Y pixel coordinate), the background level of the image, the age of the detector (trap density is thought to increase with on-orbit radiation damage), and brightness of the target. These CTE effects have been carefully quantified using observations of star clusters, and effective correction formulae have been derived (e.g., Dolphin 2009, Golimowski and Biretta 2010). By the end of the WFPC2 mission, these CTE losses could exceed 10% for bright targets, and therefore could significantly impact standard star observations.

Three factors motivated the undertaking of this study. First, it is not entirely clear how applicable CTE corrections are to standard star data: standard star observations are of a single bright star on a very faint background, while the CTE corrections were derived for fainter stars on a relatively bright background.

Second, during a recent study of WFPC2 throughput and contamination, a degeneracy arose between the CTE corrections and long-term throughput loss (i.e., the long-term decrease in throughput that was seen could be explained as either 'bad' CTE corrections on the standard star or as a genuine change in the sensitivity.

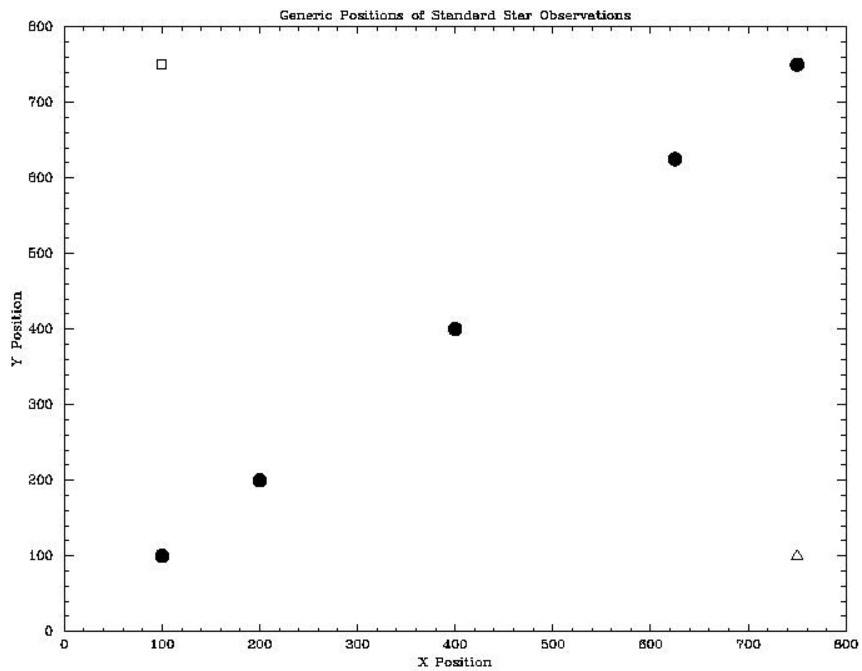
Finally, there was a possibility that the CTE is different for each of the CCDs; most of the CTE monitoring work has assumed that the CTE is the same for all of the chips and so calibration observations were designed to measure only average CTE.

Herein, we use specially designed observations to directly measure the CTE losses for GRW+70D5824 in each of the four WFPC2 detectors.

Data and Analysis

GRW+70D5824 was observed as part of WFPC2 Calibration Proposal 11804, where a total of 120 exposures were taken in the F170W and F555W filters on August 7-10, 2008. For each filter and detector, 15 observations were made. Pairs of exposures were taken along the diagonal of a chip in order to measure how the counts (DN) decreased as the distance from the readout amplifiers increased, and to allow the extrapolation of the 'CTE corrected' counts at pixel (1,1). Exposures were also taken at the remaining two corners of the CCDs in order to separate out the effects in both X and Y. See Figure 1 for the generic positions of the star on a given chip. The F170W data were all exposed for 40 seconds, regardless of which chip the star was positioned. For F555W, observations on the PC had exposures of 3.5 seconds, while those on the WF chips were exposed for 2.3 seconds. No position dithers were used; the target position on the detector was identical, to within 0.1 pixel, for the first and second (and third, for the center of the chip) exposures.

Figure 1: Generic positions of the standard star on a given chip. Two exposures were taken at each point except in the center where a third exposure was added in order to fill out the orbit. The display conventions used below (solid circles along the diagonal, open squares for low-X, high-Y, and open triangles for high-X, low-Y) will be used throughout this report.



The data were retrieved from the HST archive where they were calibrated using the latest reference files. These calibrations included a correction for the WF4 anomaly. Since 2002, a temperature-dependent reduction in the gain plagued images obtained with the WF4 detector. Characterized by low or zero bias levels, faint horizontal streaks, and low photometry, the WF4 anomaly was thought to be caused by a failing amplifier in the WF4 signal-processing electronics. Software to correct for the anomaly, as well as the associated reference files, was added to the WFPC2 pipeline in the fall of 2008. The error contributed by the WF4 corrections on the photometry is 1 to 2 percent, which is comparable to all other error sources.

The IRAF task, **DAOFIND**, was used to find the positions of the star on the chips. These positions were then used in **DAOPHOT** to determine the magnitudes of the star. While the observations were taken within a few days after the August 7, 2008 WFPC2 decontamination procedure, which improved the throughput of the WFPC2 UV filters as well as annealed many of the hot pixels, it was still necessary to account for this contamination in the F170W filter (and the F555W filter, for completeness). This was accomplished by applying the value of the ZP_CORR header keywords (separate values for each chip) to the zero points for each of the filters/chips.

The photometric uncertainties, due to photon noise, were about 0.03 magnitudes for the PC and 0.02 magnitudes for the WF chips for the F170W filter. For the F555W filter, the photometric uncertainties were 0.003 magnitudes for PC1, WF3, and WF4; while for WF2 they were about 0.004 magnitudes.

Once the magnitudes were obtained, Andrew Dolphin's (2009) CTE corrections were applied, using:

XCTE(mags)=0.0077*exp(0.50*lbg)*(1.0+0.10*yr)*x/800
YCTE(mags)=2.41*ln(exp(0.02239*c1*y/800)*(1+c2)-c2)

where:

lbg=ln(sqrt((background in $e^-)^2$+1))-1
yr=(MJD-49461.9)/365.25
c1=max(1.0-0.201*lbg+0.039*lbg*lct+0.002*lct,0.15)
c2=0.96*(yr-0.0255*yr*yr)*exp(-0.450*lct)

and

lct=ln(counts in e^-) + 0.921*XCTE - 7

These CTE corrections were derived using a 2 pixel aperture for the WF chips and a 3 pixel aperture for the PC which follows the recipe used in HSTPHOT, a photometry package for WFPC2 data by Andrew Dolphin. The corrections were then applied to the aperture photometry obtained using a 0.5" aperture.

The background for these images was calculated using the **IMSTAT** task within the region, (150:650, 150:650), so as to avoid pyramid shadows and other problem areas near the chip edges. Rejection of pixel values outside the range -10 to 20 DN, as well as sigma clipping, were used to avoid bad pixels, cosmic rays, and the star itself from being included in the background. The results showed that the backgrounds for all of the observations were nearly zero. As a result, the background was set to 0 in the lbg equation above, making its value a constant -1 for all observations.

Results

The observed counts (DN) were compared to the number of counts calculated by the **calcphot** task within the **SYNPHOT** package. Note that in order to account for the difference between the 0.5” aperture used on the observations and the infinite aperture used in **calcphot**, a correction of 0.1 mags was applied to the data. It was found that for the F555W observations, the data behaved as would have been expected: the ratio of observed to calculated counts decreased as the Y pixel value increased. The ratio was also fairly consistent between each of the chips. For the F170W observations, the behavior was not as nice, though this may be attributed to the larger noise for those data.

Figure 2 and Figure 3 show the ratios of observed to **SYNPHOT** predicted counts in each chip for both the F170W and F555W filters, respectively, *before CTE corrections were applied.* In general, the F170W data behave as expected, with the highest ratios occurring at low Y values, and lowest ratios occurring at Y ~800. But individual chips and data points show large variations. For the WF2 chip in the F170W filter, the ratios were relatively flat over the first half of the chip, then decreased slightly as Y increased. For PC1, WF3, and WF4, the ratios started out with a fairly steep decline, leveled out around the middle of the chip, fell sharply again, then began to rise for the highest values of Y. For any given Y chip coordinate, the variation between the different CCDs is approximately +/-4%.

There are may effects which could contribute to these variations. The uncertainty from photon noise in the F170W data is 2 to 3 percent, and the far UV flats probably contain an additional 1 to 2 percent residual error, which together could account for much of the variations. It is also curious that three of the four CCDs show a sharp drop between the first position (Y < 180) and the other points; errors in the first point could potentially arise from the shadow of the pyramid mirror, if this somehow affected the determination of the local sky background. PSF variations across each CCD are strong in the far UV and could also be a factor. Inhomogeneities in the F170W filter are possible, but unlikely (Lim et al. 2009).

The F555W data (Figure 3) show a much cleaner behavior. There is a smooth drop-off in counts with increasing Y coordinate, and it reaches about 15% loss near Y ~800. At any given Y position, there is a +/- 1% to 2% variation between the different CCDs.

Figure 2: Ratios of observed to calculated counts for F170W - no CTE corrections were applied.

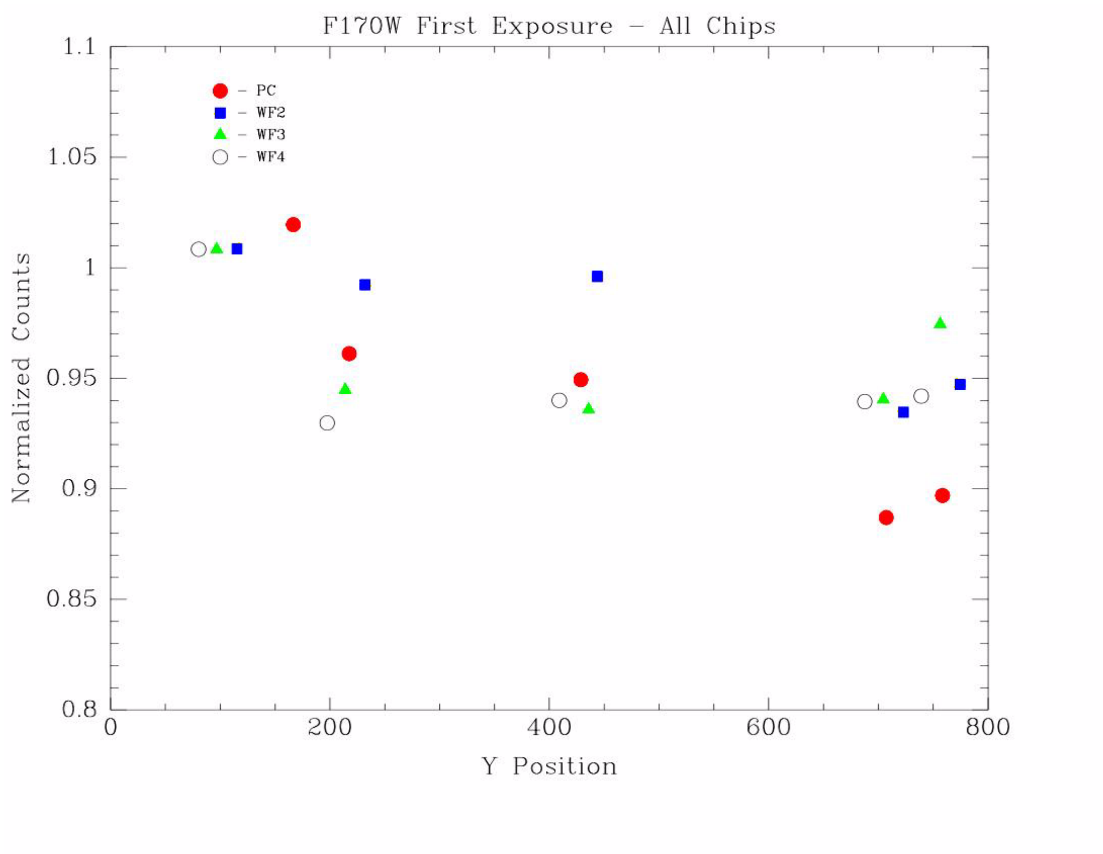
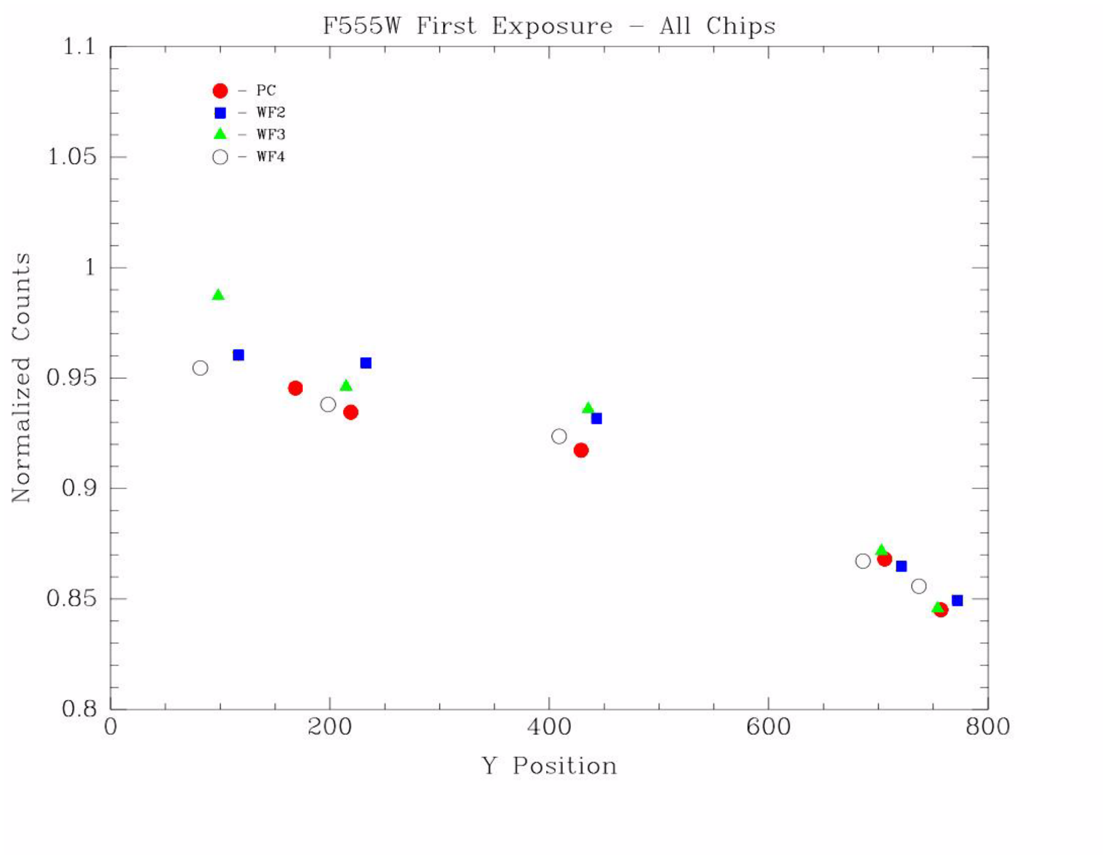


Figure 3: Ratios of observed to calculated counts for the F555W filter - no CTE corrections were applied.



First Exposure Effect

At each position on a detector, two exposures were taken in rapid succession. A third exposure was also taken at the center (Y ~400) position. One of the most striking results was the difference in the number of counts (DN), and subsequently the magnitudes, between the first and second exposures of the star. Figure 4 and Figure 5 illustrate the differences seen between the first and second exposure for observations in the F170W and F555W filters, respectively. The first exposure nearly always recorded fewer counts than the subsequent exposure(s). These differences are dependent on the Y pixel, and increase as Y increases. The differences are near zero for the lowest values of Y, and reach 4% to 6% as Y approaches 800. It appears that, in effect, the first exposure is pre-flashing the subsequent exposures. Little difference (about 1%) was seen between the second and third exposures.

The time between exposures was 2 minutes - apparently it is possible for traps in the CCDs to remain filled for some time after an exposure. Previous studies of residual images in the WFPC2 detectors indicated that the half-life for the release of trapped charge was ~11 minutes (Mutchler and Biretta 1997), though it is not clear whether the traps responsible for residual images also contribute significantly to CTE losses. Shorter timescale traps (few seconds or less) are clearly responsible for the CTE tails seen on hot pixels, cosmic rays, and bright targets (Biretta and Kozhurina-Platais 2005).

Many further details of this phenomenon are not known: how much delay between the exposures can occur before the effect is no longer seen? How much position change between the exposures can there be before this effect is no longer seen? Much as CTE increases for fainter targets (increased magnitude error), does the first exposure effect also increase for fainter targets? Data were taken to further quantify the effect in visits 36 to 39 of proposal 11804, but analysis and study of these data are left to the future.

Figure 4: Differences between the first and second exposures (second exposure counts divided by first exposure counts) for observations taken in the F170W filter.

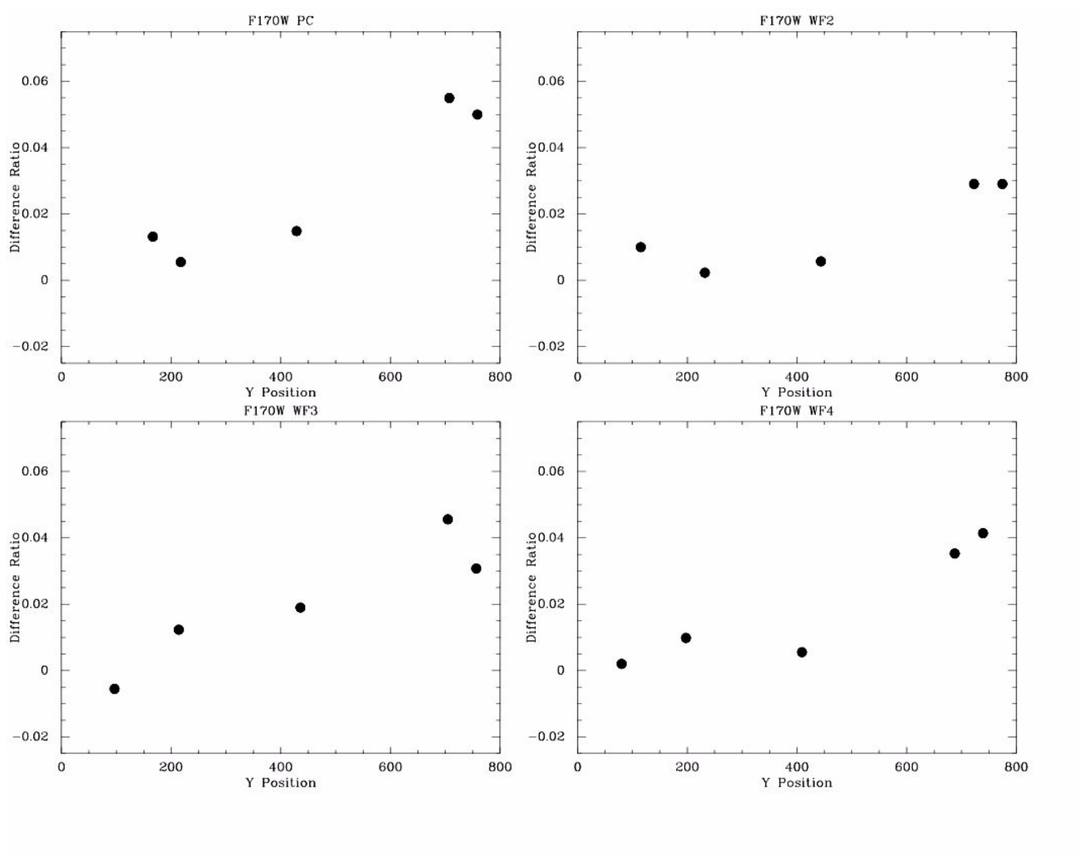
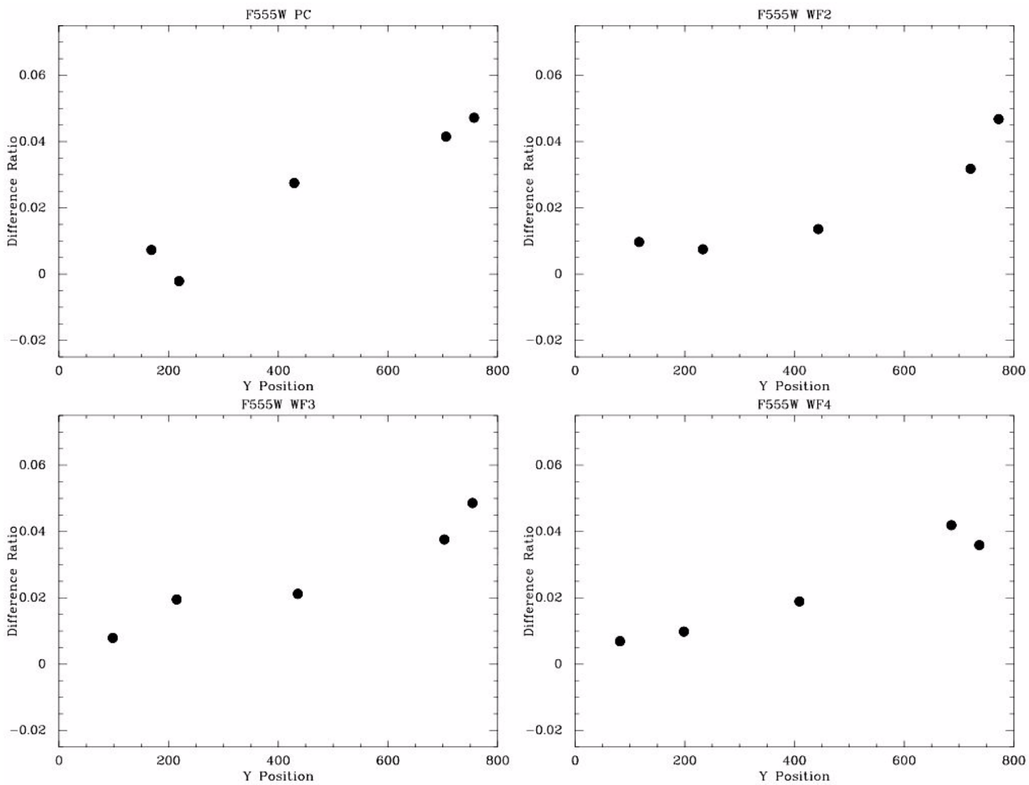


Figure 5: Differences between the first and second exposures (second exposure counts divided by first exposure counts) for observations taken in the F555W filter.



CTE Corrections

As stated above, the CTE corrections were derived using a two pixel aperture for the WF chips and a three pixel aperture for the PC and then applied to a 0.5” aperture (about 5 WF pixels and about 11 PC pixels). The question then became not only how well the above equations corrected the CTE but on which exposure, first or second, did the corrections do a better job.

Once the CTE corrections were applied to the data, the results were compared to the values generated by the **calcphot** task in the **SYNPHOT** package. The **calcphot** results were CTE-free (no CTE correction needed to be applied) and at an infinite aperture. Again, a correction of 0.1 mags was applied to the data in order to account for the difference between the 0.5” aperture used in the photometry and the infinite aperture used in **calcphot**.

The counts determined from the data were normalized to those generated from **calcphot** and a linear fit was applied. The results are shown in Figures 6-9. Figure 6 and Figure 7 show the results for the F170W data. While the data for the PC chip appear to have a good correction, it is easy to see that the data for the WF chips are over-corrected. The over-correction, averaged across the WF chips, reaches about 7% for Y=800 in the first exposures.

For the second exposures, the PC appears to be about 6% over-corrected at Y=800, as might be expected from the first exposure result and the 'first exposure effect' discussed above. For the WF chips, the second exposures are about 13% over-corrected at Y=800.

Typically, the star would be placed near the center of the CCD (Y ~400) for standard star observations, and hence the residual CTE effects would be about 3% for first exposures, and about 6% - 7% for second exposures, both in the sense of being over corrected by the standard Dolphin equations.

Figure 6: F170W CTE Corrected Data for the First Exposure

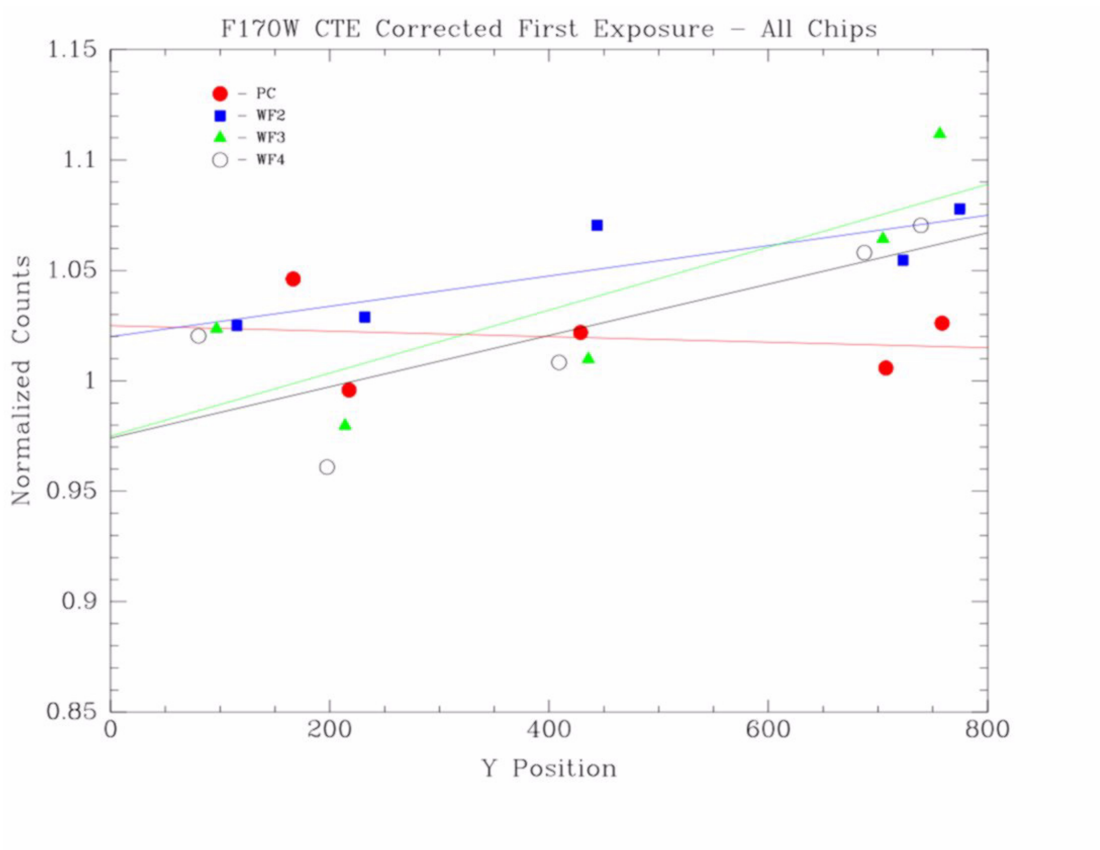


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Figure 7: F170W CTE Corrected Data for the Second Exposure

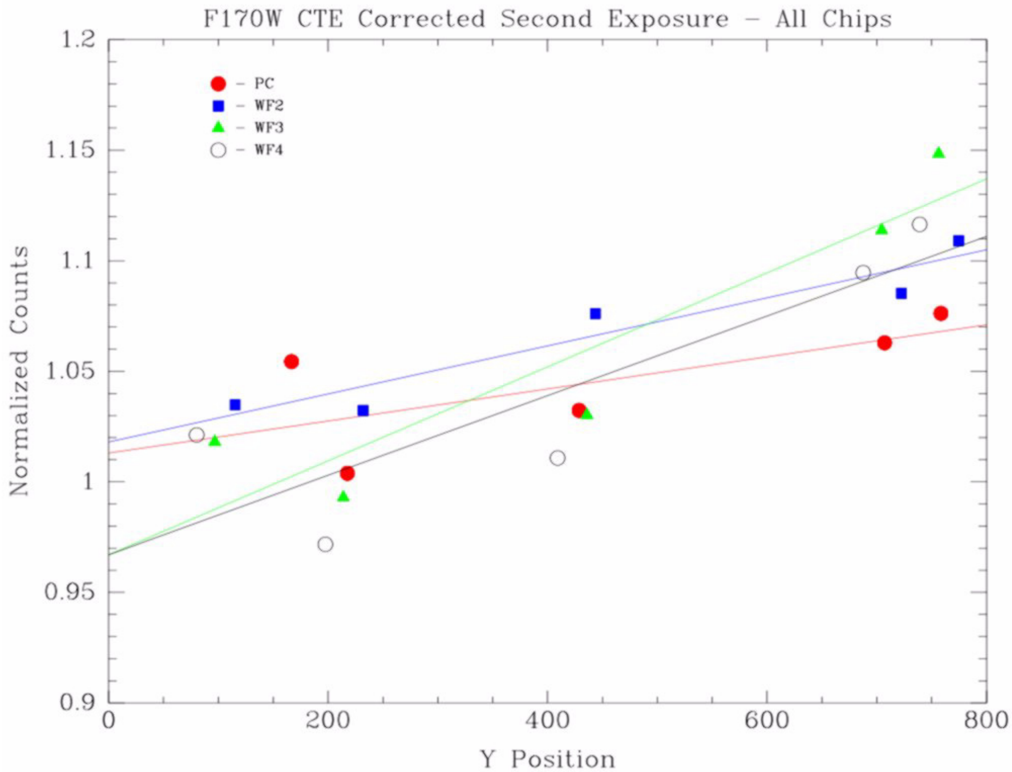

Table 1. Parameters for Linear Fits for F170W Data

Exposure	CCD	Intercept (Y=0)	Slope (Delta Y=800)
1st	PC	1.025	-0.010
1st	WF2	1.020	0.054
1st	WF3	0.975	0.115
1st	WF4	0.974	0.093
2nd	PC	1.013	0.058
2nd	WF2	1.018	0.087
2nd	WF3	0.967	0.170
2nd	WF4	0.967	0.144

Figure 8: F555W CTE Corrected Data for the First Exposure

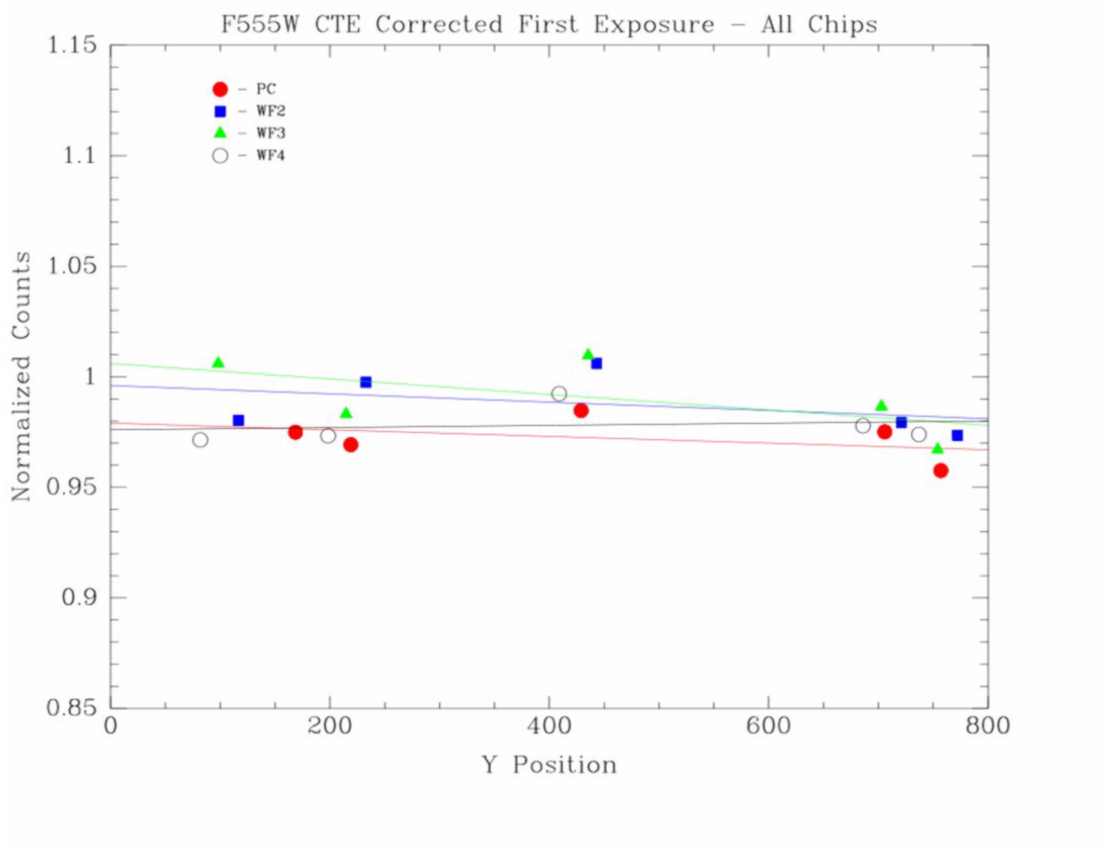

Figure 9: F555W CTE Corrected Data for the Second Exposure

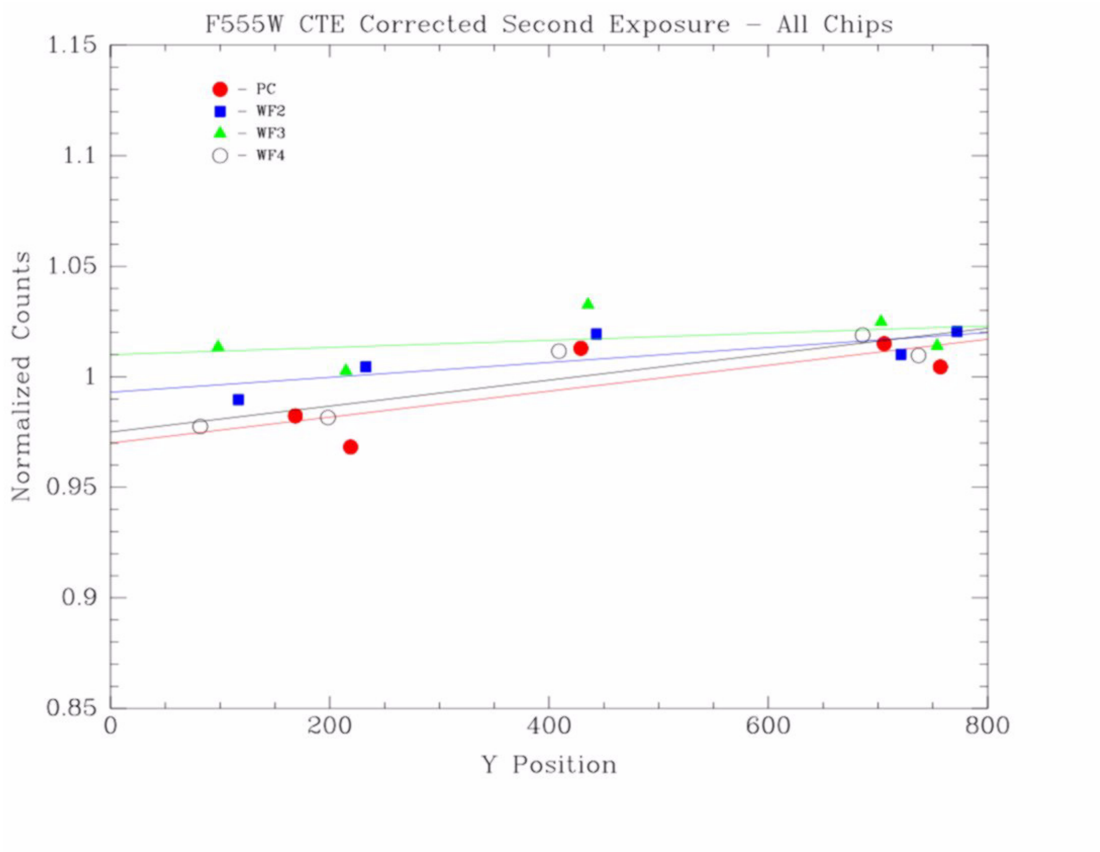

Table 2. Parameters for Linear Fits for F555W Data

Exposure	CCD	Intercept (Y=0)	Slope (Delta Y=800)
1st	PC	0.979	-0.011
1st	WF2	0.996	-0.016
1st	WF3	1.006	-0.029
1st	WF4	0.976	0.004
2nd	PC	0.970	0.047
2nd	WF2	0.993	0.027
2nd	WF3	1.010	0.013
2nd	WF4	0.975	0.047

Similar to what was seen for the uncorrected case, the results for the F555W show a much tighter distribution (confined to a much narrower band of the plot) than those for F170W.

This is due in large part to the smaller photon noise in F555W, as well as the higher quality of the flat fields in F555W.

For the first exposure observations (Figure 8), the data are slightly under-corrected: the slope of the ratio of observed counts to **SYNPHOT** predicted counts is slightly negative. The four chips average about -1% slope across the 800 rows. In detail, the fit for WF4 is nearly flat, while PC1, WF2, and WF3 lose slightly more than 1% of the counts across Y=800. Since many of the standard star observations were done near the CCD centers, the impact of this under-correction on photometric calibrations would have been quite modest, about 0.5% error and similar to other error sources.

It is somewhat interesting that WF4 appears to have good correction for CTE (nearly flat slope), while the other chips are under-corrected. Evidence for lower CTE in WF4 has been reported elsewhere (Biretta and Kozhurina-Platais 2005, Golimowski and Biretta 2010)

At the chip centers, the average ratio of observed to **SYNPHOT** predicted counts in Figure 8 is very close to unity, and all individual chips are within about 1% of unity. But this is to be expected: the values of `ZP_CORR` (which have been applied to our data), are computed to insure this condition. So this agreement between the observed and **SYNPHOT** counts merely implies the machinery for generating `ZP_CORR` values has worked properly. It does not necessarily tell us anything about CTE issues; instead, that information is contained in the slope of the values versus CCD position.

As might be expected from earlier discussions, the second exposures (Figure 9) are over-corrected, and the slope across all 800 rows is approximately 3%. At Y ~400, where standard star observations are often made, the error from these residual CTE effects would be about 1.5%.

Discussion

From the results presented, it is clear that issues are present when applying the Dolphin CTE corrections to standard star observations. In the case of the F555W filter, the residual errors are relatively small, being about 0.5% at the chip centers for the first exposures, and about 1.5% for the second exposures.

Much more serious errors appear to be present for the UV filters, where count levels and backgrounds are lower. For the F170W filter, the residual errors at the chip centers are about 3% for the first exposures and 6% to 7% for the second exposures, both in the sense that the results are over-corrected for CTE effects. Presumably, other UV filters with similar count rates would suffer similar effects in their standard star data.

The determination of whether a given standard star observation would behave as a ‘first’ or ‘second’ exposure is likely to be a complex question. The majority of the standard star observations are obtained by leaving the star at a given place near the center of the chip, and then cycling through the different filters in rapid succession. For this reason, we might expect the majority of the standard star observations to behave as second exposures, and therefore suffer the larger residual CTE errors for second exposures noted above.

However, several effects probably cause more complex behavior. For example, small wedges in the filter glasses can cause small spatial offsets on the detectors when the filters are changed. Also, small pointing errors may be present during long sequences. Such pointing offsets would make exposures in a sequence more like first exposures. In the observations made here, all exposures in a sequence (first, second, etc.) had the same duration and filter, and hence total counts, but actual observations of standard stars will have a sequence where the filters and count rates are changing between each exposure. Hence, an actual standard star observation could fall somewhere between the 'first' and 'second' exposure cases (or suffer stronger 'second' exposure errors), depending on whether the prior exposure had fewer (or greater) counts. The exact behavior will likely depend on all these effects: filter wedge, pointing offsets, and counts in the prior exposure.

Additional study will be needed before we can accurately assess and correct for CTE in the standard star data. Until then, it may be most prudent to treat these errors in the CTE correction as an additional source of uncertainty in the standard star data: perhaps 1% to 2% for well-exposed in the visible filters such as F555W, and as much as 6% to 7% of additional uncertainty for UV filters like F170W, for observations taken late in the WFPC2 mission. While not well established, it is reasonable to assume these uncertainties would scale linearly with epoch (as do the CTE corrections), and be correspondingly smaller early in the WFPC2 mission.

The 'first exposure effect' has a number of implications for data taken late in the WFPC2 mission. It will cause the first exposure in a non-dithered sequence to have about 4% to 6% lower counts than subsequent exposures at Y=800. The average effect over the CCD (and that at the CCD centers) will be about half this. The effect also implies that photometry will depend in part on the prior state of the CCD pixels. For example, a pixel hit by cosmic rays during earth occultation, between exposures, or during a prior exposure, will record higher counts for a target than the rest of the CCD array for the next exposure.

For data taken early in the WFPC2 mission, say before 2003, presumably the first exposure effect would scale with other CTE effects and be less than half these amounts: 2% to 3% at Y=800, and 1% to 1.5% averaged across the field of view. At these levels it would be comparable to other error sources and not very serious.

Conclusions

Observations of the WFPC2 standard star, GRW+70D5824, were used to study the effectiveness of the Dolphin CTE correction formulae for standard star data. We found that the equations aren't entirely suitable for these types of observations (short exposures of a single star). For the F170W data, the equations over-correct the photometry by up to

6% to 7% at the CCD centers. For F555W, the correction equations perform better: the data are under-corrected by about 1% to 2% at the CCD centers.

We have also found a very significant ‘first exposure effect’ where the first exposure of a non-dithered sequence will have 4% to 6% lower counts than subsequent exposures for targets at Y=800 (and about half this effect at chip centers). This effect could be an important error source for data taken late in the WFPC2 mission, as the photometric results will depend on how the data were taken (dithered vs. non-dithered) and on the state of the CCD pixels prior to the science exposure (cosmic rays during idle time, etc.). A more detailed approach to CTE corrections, such as pixel-based CTE corrections currently under investigation by the ACS/ WFPC2 Team, may be needed.

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