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Charge Transfer Efficiency for Very Faint Objects and a Reexamination of the Long-vs.-Short Problem for the WFPC2

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Abstract. An analysis of WFPC2 observations of Omega Cen and NGC 2419 leads to the following results.

1. The correction formula developed by Whitmore, Heyer, and Casertano (1999; hereafter WHC99) does a reasonable job of correcting for CTE loss down to extremely low count levels. There is no sharp cutoff to the detection threshold for very faint stars.
2. A comparison of the WHC99 formula with the Dolphin (2000; hereafter D00) formula shows reasonable agreement for bright and moderately bright stars, with the D00 formula giving better results. However, at very faint levels, the D00 formula overestimates, and the WHC99 formula underestimates, the correction by tens of percent. *Note: Our current recommendation is to use the new Dolphin 2002 (hereafter D02) formula for CTE loss correction, which is an improvement on the D00 formula.*
3. A reexamination of the long-vs-short nonlinearity shows that the effect is very small (a few percent) or nonexistent for uncrowded fields, with less than ~1000 stars per chip. However, for crowded fields, with ~10,000 stars per chip, apparent nonlinearities of tens of percent are possible. We believe this is due to difficulties in measuring the sky values for the short exposures.
4. Preflashing may be a useful method of reducing the effects of CTE loss for certain observations (moderately bright objects on very faint backgrounds), but the effects of added noise and longer overheads limit its effectiveness.
5. The detection thresholds for typical broad band observations have been reduced by ~0.1–0.2 mag in the ~9 years since WFPC2 was launched. For worst-case observations (F336W) the effect is currently ~0.5 magnitudes.

1. A Comparison of WHC99 and D00 CTE Correction Formulae

The Charge Transfer Efficiency (CTE) of the WFPC2 is declining with time, as first shown by Whitmore (1998). By February 1999, for worst case observations (very faint objects on very faint backgrounds) the effect of CTE loss from the top of the chip had reached levels of ~40% (WHC99). For more typical observations, CTE loss was 5–6% by this date. Formulae have been derived by various groups to attempt to correct for the effects of CTE loss (WHC99; Saha, Lambert & Prosser 2000; D00). Various techniques are currently being studied to minimize the effect of CTE loss on new HST instruments (ACS and WFC3 include preflash capabilities).

D00 examines CTE loss by comparing WFPC2 observations with ground based observations of Omega Centauri and NGC 2419, using a baseline through March 2000, roughly a year longer than available for an earlier study by WHC99. In general, D00 finds good agreement with the WHC99 results, and the longer baseline and more extensive data set used

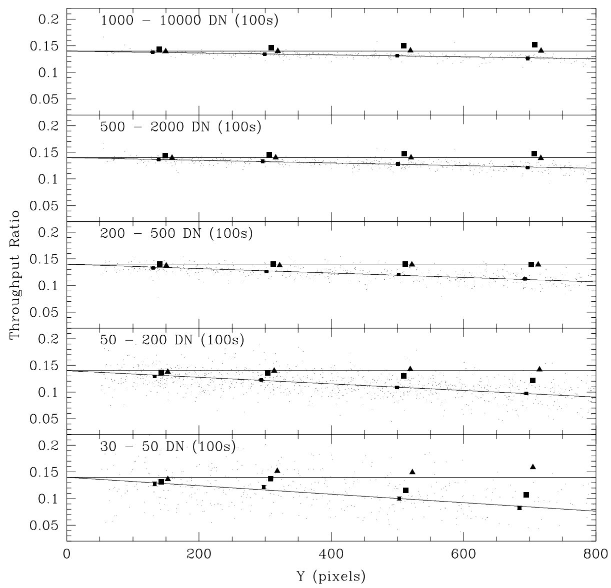

Figure 1. This shows the ratio of counts between a 14 sec and 100 sec exposure for stars in Omega Cen vs. the Y position for stars on all three WF chips. The raw values (filled circles) fall below a ratio of 0.14 due to CTE loss. The different panels are for different target brightness, as selected on the 100 sec exposure and described by the labels. The filled squares show the values corrected using the Whitmore, Heyer & Casertano (1998) formula while the filled triangles show the values corrected using the Dolphin (2000) formula. Note that neither of the two correction formulae is very good for the faintest stars (∼5 DN on the short exposure). Also note that the extrapolation of the raw data to $Y = 0$ (the sloped line) is consistent with the predicted value of the throughput ratio based on the exposure times, hence the long-vs.-short anomaly is not a problem for this data set (from Dolphin 2002). Dolphin has recently updated his formulae to improve the agreement for the faint stars.

by D00 result in less scatter in the residuals. In particular, D00 finds similar corrections to within a few hundredths of a magnitude in almost all cases.

The details of this study can be found in Whitmore and Heyer (2002), available at `http://www.stsci.edu/instruments/wfpc2/Wfpc2_isr/wfpc2_isr0203.html`

2. A Reexamination of the Long-vs.-Short Anomaly

Suggestions of a long-vs-short photometric nonlinearity between short and long exposures was first discussed by Stetson (1995), and then examined in more detail by Kelson et al. (1996) and Casertano and Mutchler (1998). More recent studies, however, have found less evidence for the existence of the "long-vs.-short" problem (Dolphin 2000). Dolphin (2000) suggest that the apparent long-vs.-short anomaly may be caused by overestimating the value of the sky by a few electrons in the shorter exposure.

It has been suggested that the long-vs-short anomaly may be caused by difficulties in measuring the sky on very crowded images. We can address this question by separating the measurement of the local sky and the measurement of the object. The top left in Figure 2 shows a measured slope consistent with the normal CTE effect. The intercept at $Y = 0$ is 0.00985 ± 0.00012, very near the theoretical value of 0.01. Hence, there appears to be little or no long-vs-short problem for the ratio of the object observations. However, the ratio of

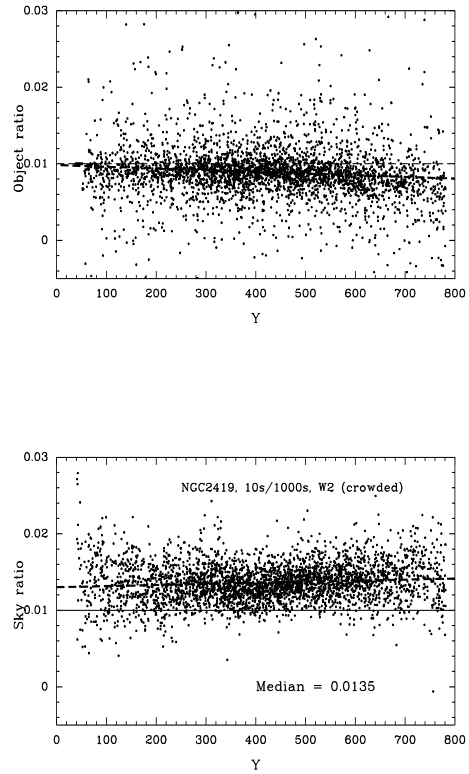

Figure 2. The ratios of the counts in the 10 sec exposure to the counts in the 1000 sec exposure for the crowded NGC 2419 field (left side). The top panel shows the ratios in the object apertures using a constant sky value of 0.30 DN for the short exposure and 30 DN for the long exposure. The bottom panel shows the ratio for the local sky measurements. The sky ratio is well above the predicted value of 0.01, demonstrating that the long-vs.-short effect is caused by the sky measurements rather than the object measurement. The dashed line shows a least squares fit for the object ratio data.

the local sky values (as measured in an annulus between 5 and 10 pixels) shows a obvious tendency to be above the theoretical value of 0.01, with a median value of 0.0135. This appears to be the cause of the long-vs.-short anomaly in this data set; the sky values in the 10 sec exposure appears to be overestimated by about 35%, relative to the predicted value based on the sky measurement of the 1000 sec exposure. See Whitmore et al. (2002) for more details and a possible explanation for this discrepancy.

3. Detection Threshold as a Function of Time

The CTE correction formulae can be used to estimate the evolution of the degradation in S/N for stars due to CTE loss as a function of time, and hence allow us to determine how the detection threshold (defined at S/N = 10) evolves. We show an estimate of S/N for a 1000s exposure using the F555W filter for a typical observation with a background of 50 electrons. We assume aperture photometry with object/inner-sky/outer-sky values of 2/5/10 pixels. Noise components are read noise (5 electrons/pixels), Poisson noise, and the uncertainty in the CTE formula (25%, based on a comparison of the WHC99 and D00 formulae).

Table 1 shows the Signal-to-Noise at various magnitudes for a 1000s exposure using the F555W filter at the top of the chip (i.e., $y = 800$ pixels). This represents the worst case. The CTE effects are essentially half as large for a random distribution of objects (with mean $Y = 400$ instead of $Y = 800$). Table 2 shows the limiting magnitudes for the V and U bands for a 1000s exposure.

Table 1. Signal-to-Noise at Various Magnitudes for a 1000s Exposure

V mag	04/24/1994	2000	2005	2010
22.0	103.1	102.2	101.5	100.8
23.0	67.4	65.7	64.4	63.0
24.0	39.9	38.0	36.5	35.1
25.0	21.2	19.5	18.3	17.2
25.5	14.7	13.4	12.4	11.5
26.0	10.0	9.0	8.2	7.5
27.0	4.4	3.8	3.4	3.0

Table 2. Limiting Magnitudes for Two Different Filters in 1000 Seconds

Date	V-Mag	delta	U-mag	delta
04/24/1994	26.00		23.16	
2000	25.87	0.13	22.81	0.35
2005	25.76	0.24	22.59	0.57
2010	25.67	0.33	22.40	0.76

4. To Preflash Or Not To Preflash...

CTE loss can be reduced by increasing the background, hence filling some of the traps before the target reaches them. One can artificially enhance the background by adding a preflash. This removes the dependence on CTE correction formulae, which introduce their own uncertainties. The problem with this approach is that it also adds noise. Figure 3 shows a calculation based on the WHC99 correction formula, assuming a very low background for the raw image (0.1 electron, appropriate for a very short exposure, a narrow-band exposure, or an exposure in the UV) versus an exposure which has been preflashed with 25 electrons. The ratio of the S/N for the preflashed image versus the raw image is plotted vs. the Log of the target brightness. The three curves show the effects for a star near the bottom of the chip ($X = 400$, $Y = 100$, where the preflash is never an advantage since CTE loss is low and the preflash adds noise), near the center of the chip, and near the top of the chip (where the preflash is an advantage for the brighter targets). Therefore, for fainter targets there will be nothing gained by preflashing, while for brighter targets, the amount of gain will depend on the location on the chip.

An additional factor to consider is that the preflash exposure requires 2–5 minutes of overhead per exposure (depending on the necessity of filter changes and read-out, and length of the preflash exposure). In some cases these internal flat preflashes can be taken during occultations by the Earth, hence not affecting the effective integration time. The effect of the overhead time has not been included in the calculation since the exposure time for a given target will vary. However, for the typical case of two 1000 sec exposures per

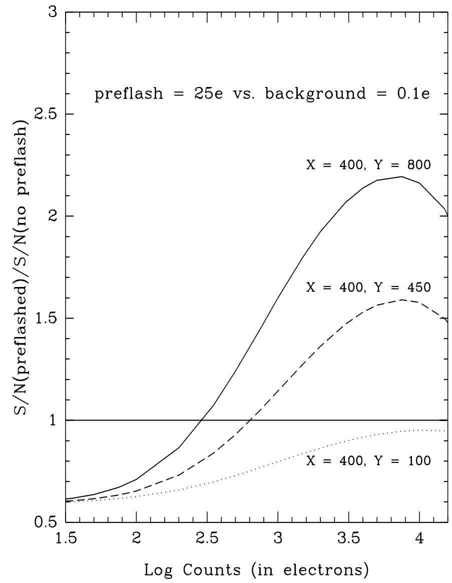

Figure 3. Calculation based on the WHC99 correction formula, assuming a very low background for the raw image, versus an exposure which has been preflashed with 25 electrons.

orbit, with the first preflash being taken during the occultation, the result would generally be that only two 900 sec exposures would fit into one orbit, resulting in a decrease of ∼5% in the S/N, and ∼0.1 mag in detection threshold (assuming the noise is dominated by Poisson statistics; the effective change would be smaller if other sources of noise dominate). For shorter exposures the effect can be much larger, especially since a smaller percentage of the preflash exposures can be taken during the occultation. For example, for 3 minute exposures the S/N would be diminished by ∼40%, offsetting any advantage of a preflash over nearly the entire chip, even for best-case-scenarios.

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