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# ACS CCD Gains, Full Well Depths, and Linearity up to and Beyond Saturation

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**ABSTRACT**

*The CCDs on ACS may both be operated at multiple gain settings. Analysis of calibration and science data is used to establish corrections to the supported HRC GAIN=4 and WFC GAIN=2 values; relative to the default gains decreased values of e-/DN of 1.27% and 0.78% respectively are indicated. Maps of the full well depth at which saturation sets in for both HRC and WFC are provided, both cameras show spatial variations in excess of 10%. When operated with gains that fully sample the full well depth, the CCDs remain perfectly (<0.1% relative count levels) linear to well beyond saturation with simple summation over pixels that have been bled into as a result of over-saturation. Linearity at levels from marginal detection in single exposures, to multiple levels up to saturation, and at multiple levels beyond saturation are presented showing excellent results.*

## Introduction

The ACS CCDs have default gain values of approximately 1 e-/DN (WFC) and 2 e-/DN (HRC) -- these settings have, in particular, been used to establish adjustments to basic quantum efficiency curves. Minor errors in the default gain values would therefore be absorbed into revisions of the QE curves. There is no compelling reason to seek refinement in the quantitative values of gain at the default levels used for primary calibrations and the bulk of the science program.

The default gains do not sample the full well depths of the CCDs, falling short by about 35% (WFC), and 22% (HRC). Use of the next higher gain values of approximately

2 e-/DN (WFC) and 4 e-/DN (HRC) do provide full sampling of the roughly 85,000 e- and 165,000 e- full well depths respectively. Since the readout noise is only marginally higher than with the default gains, and the readout noise is well-sampled (true for WFC, not quite for HRC, but even here it's much better than for any WFPC2 data ever taken) even at these higher values, many science programs and calibration programs may logically choose these gains. Through analysis of observations of the same stellar field, in the same filter and at the two gain settings it is possible to obtain an accurate adjustment of these gain values relative to the default gain levels. The results here will supply these to better than 0.1%, removing errors that average about 1% for the two cameras.

The spatial variation of CCD full well depths for both cameras may be quantified by noting count levels in the cores of stars as they transition to saturation. Direct knowledge of this spatial dependence is provided for completeness, although this seems to be primarily of academic interest.

A surprising result from early calibrations of the STIS CCD was that with use of a GAIN that samples the full well depth, the response remains linear not only up to saturation, but from simply summing the counts over pixels bled into during saturation, the counts remained linear to well beyond saturation (Gilliland, Goudfrooij, and Kimble 1999). A similar result, albeit at necessarily lower levels of precision, had been demonstrated for WFPC2 (Gilliland 1994). The ACS CCDs have proven to be as well behaved as the STIS CCD -- electrons are clearly conserved after saturation occurs. It is possible to easily perform photometry on point sources that remain isolated simply by summing over all of the pixels bled into, but this will only work if a gain has been selected that directly samples the full well depth. Given the extra dynamic range afforded before saturation at GAIN=2 (WFC) and GAIN=4 (HRC), and the only modestly increased readout noise, coupled with the potentially beneficial aspect of being able to recover photometry on saturated objects, more frequent use of these gains may be appropriate.

## Observations

Accuracies for relative calibrations of gains, and for testing linearity generally need to be quite high with a general goal of reaching better than 0.1%. Such accuracies are best obtained through simple differential comparisons. An ideal case for comparing gains would be back-to-back observations of the same target at the two gain values. For testing linearity the need is for back-to-back exposures at different exposure times, and for which the shortest exposure time is long enough to not be uncertain by more than 0.1% (for the WFC this is 10 seconds, 2 seconds suffices for the HRC -- see Gilliland and Hartig 2003). Data satisfying the above constraints on a moderately rich star field will automatically be very useful for the additional steps of defining full well depth maps and for general investigations related to linearity.

Data from the following programs have proven to be most useful:

1. GO-9433. The GO used the 47 Tuc L-flat field to acquire PSFs for his F606W exposures and acquired two sets (January 13, 2003 and February 9, 2003) of 10s, 340s WFC observations at GAIN=2. These data are ideal for mapping full well depths and for testing relative linearity over a broad dynamic range, including to well beyond saturation.

2. GO-9443. This is the King and Anderson outsourcing program for geometric distortion. They use the core of 47 Tuc and by good fortune for these tests happened to take back-to-back F475W exposures of 60s at GAIN=1 and 150s at GAIN=2 for the WFC (July 7, 2002) and 2x60s at GAIN=2 and 350s at GAIN=4 for the HRC (July 24, 2002)-- ideal for testing the ratio of these two gains. The data also support general linearity testing and definition of full well depth.

3. CAL-9018. A pair of WFC exposures in F606W were acquired with 2x22.5s each, once with GAIN=1 and once at GAIN=2 (same field, but taken one month apart on April 19 and May 9, 2002 these had a slightly different roll angle). These are ideal for verifying the gain ratio. These are also useful for testing for non-linearity at low intensity levels in comparison to single, much longer exposures available at each epoch. At these early dates CTE is expected to be small.

4. CAL-9019. Pairs of HRC exposures in F435W were obtained on the core of 47 Tuc with integration times of 5, 20, and 300 seconds dating from April 13, 2002. These GAIN = 2 exposures are nearly ideal for a test of linearity at low signal levels.

5. CAL-9560, the Cycle 11 interim calibration program with two dedicated orbits on 47 Tuc to explore issues of linearity and to establish the relative gain values. This provides a broader range of data supporting derivations of gain values, including the available-but-unsupported GAIN=4 (WFC) and GAIN=1 (HRC) for which some archival science data exists. These observations were taken May 18, 2002.

6. CAL-9662, the Cycle 11 shutter stability test was originally planned to also support linearity tests; the HRC exposures for this are useful. The WFC exposures (obtained with the CLEAR filter) proved adequate for establishing shutter timings, but are generally not useful for linearity checks given higher than anticipated sensitivity to telescope breathing as a result of the slightly out-of-focus PSFs.

Taken together about 40 images culled from the above programs provide a robust basis for establishing measurements related to gain ratios, full well depths, and linearity at both low and high signal levels.

## Gain Adjustments

The gain values in use between instrument installation on-orbit and now can be traced to ground test results. The primary tool for measuring gain values is the “photon-transfer method” which is described in the Appendix to Martel, Hartig, and Sirianni (2001a).This technique relies on analysis of identical exposure pairs of flat-fields taken at a range of intensity levels. The relation between differences of intensity values (noise) and the direct signal level over an ensemble of pixels at a given exposure level depends on the readout noise and the gain, the relation can be fit at a range of intensity levels to uniquely determine these two quantities. This technique can also return information of limited utility on linearity (depends on constancy of lamp source, or experimental techniques to control for drifts) and the count level at which saturation sets in (may be different for uniform illumination than for point sources) by determining where the photon-transfer curve departs from linearity at high signal levels. Errors of about 0.6% in the gain values are quoted for the WFC determinations, and similar values hold for the HRC as given in Martel, Hartig, and Sirianni (2001b).

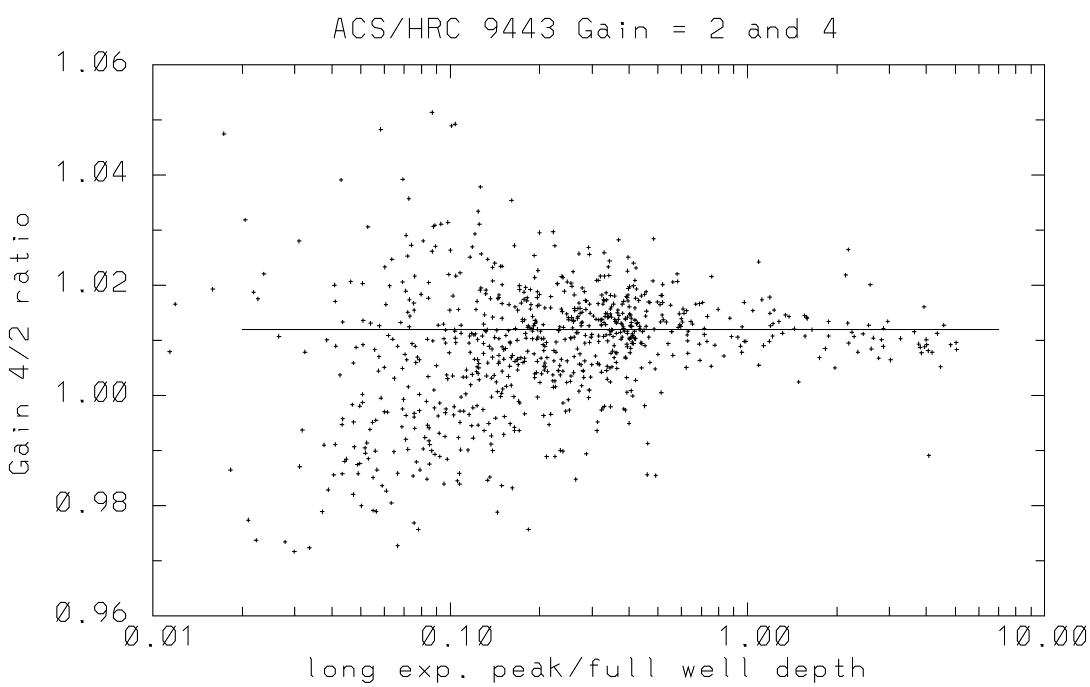
On the WFC, with two CCDs and the default use of two amplifiers per CCD, errors of 0.6% in the normalization of gains quadrant-to-quadrant would leave easily visible steps in observations of spatially flat sources. Bohlin, Hartig and Sparks (2002) provide a redetermination of the WFC gains, maintaining the same mean over all amplifiers at a given gain setting, but using a continuity constraint across quadrant boundaries to provide an improvement in amplifier-to-amplifier gains at better than 0.1%. The study in this ISR will use on-orbit data to redetermine the mean absolute gain values to better than 0.1%, relative to a standard adopted for the default gains on each camera, e.g. WFC GAIN=1 and HRC GAIN=2 values are retained, and other gains adjusted relative to these. Absolute errors of about 0.6% could remain in the default gain values, but these are of no real consequence since redetermination of the CCD quantum efficiency would compensate for this since the QE adjustments were based on data acquired with the default gains. Adjustments derived herein will not require redetermination of other related factors (e.g. QE or L-flats), but will assure that basic photometric calibrations apply with equal accuracy to data acquired at all supported gains.

***High Resolution Camera.***

In the CAL-9560 HRC exposures on 47 Tuc a total of 9 unsaturated stars were identified to compare across otherwise identical observation sets taken at different gain values. In the **crj** extension files the count levels provided by CALACS in e- should be exactly the same independent of gain. The extent to which this is not true provides the updated gain value. At each of GAIN = 4, 2, 1 exposures of 5x10 seconds were acquired with CR-SPLIT=5 yielding root names of j6ko01021, j6ko01031, and j6ko01041 respectively. Before evaluating counts in stars local sky levels are evaluated and subtracted. Apertures with radii of 6 and 9 pixels were tried with no difference resulting. The ratio of counts in the CALACS processed GAIN = 4 observation ratioed to the GAIN = 2 standard is 1.0131 +/- 0.0010 standard error. The ratio of counts in the CALACS processed GAIN = 1 observation ratioed to the GAIN = 2 standard is 1.0192 +/- 0.0010.

The GO-9443 observations were obtained on the core of 47 Tuc providing a much larger number of stars from which the GAIN = 4 value relative to GAIN = 2 can be derived. The two 60s HRC observations with F475W obtained with REPEAT-OBS have been processed locally with crrej to eliminate cosmic rays in an average combined image. The 350 s HRC observation is shifted by 0.1 pixel with respect to the combined 60 s image; account has been taken of this in projecting an expected image at the position and increased time of the 350 s image, cosmic rays are then eliminated as greater than 4 $\sigma$ positive deviations of the real to projected long image. In this approach to cosmic ray elimination pixels that saturate and the nearest neighbors to these must be retained. Relative sky values between the respective 60 s and 350s images are evaluated by selecting a mask of pixels in one image that fall near the sky median, then evaluating the mean in each image for the identical set of pixels. The resulting ratio of sky values was very close to ratios derived from well exposed stars. These global sky values are subtracted from each image. Stars have been selected with peak counts between 10,000 and 25,000 e- in the 60 s exposure that will not saturate in the 350 second exposure. The same aperture of radius 7 pixels is used to extract summed intensities in each image. Stars are not used if bleeding trails approach within 8 pixels of the star centers. A total of 108 stars are used to form a mean ratio of GAIN = 4 to GAIN = 2 count levels of 1.0127 +/- 0.0004. Figure 1 shows results for a much larger range of stellar brightness, the set used here fall roughly between 0.5 and 1.0 on the x-axis; these results will be discussed further under linearity below.

**Figure 1:** The x-axis shows the expected peak counts in the long 350 second HRC exposure based on scaling up from unsaturated stars in a 60 second image, and then ratioing to the spatially dependent CCD full well depth. Values in excess of 1.0 are saturated stars in the long exposure. The ordinate shows the ratio of aperture-summed counts in the long exposure relative to the short with the relative exposure time taken out, deviations from unity show relative error in the assumed gain values. The horizontal line at 1.0127 shows the adopted correction factor for GAIN=4 relative to the default GAIN=2 value.



The two independent determinations of GAIN = 4 are in near perfect agreement. The current GAIN = 4 value using the default AMP C is 4.289. Correcting by the factor of 1.0127 yields a proper GAIN = 4 value of 4.235 which is estimated to be accurate to better than 0.1% relative to the GAIN = 2 standard. For GAIN = 1 (less important since this is available-but-unsupported) the single determination at 1.0192 results in changing the current value of 1.185 to 1.163 (also accurate to about 0.1%).

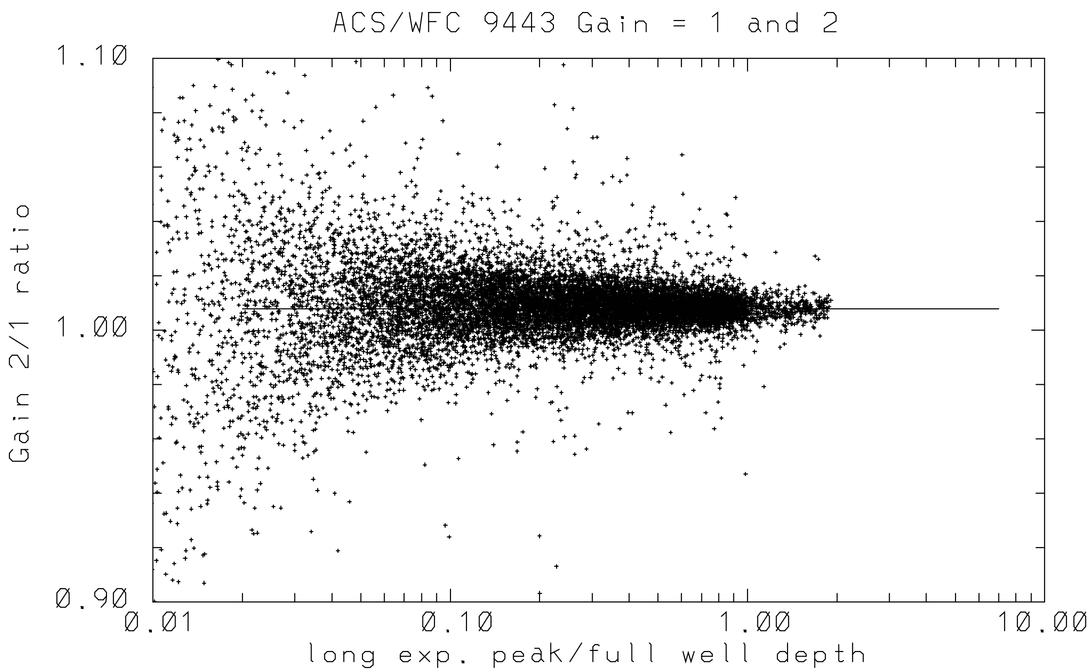
***Wide Field Camera.***

The CAL-9560 exposures with the WFC were obtained with a 1024x1024 subarray defaulting to use of AMP A, therefore derived gain ratios are only for this one amplifier. At the standard GAIN = 1, 4x12 second exposures were taken, and appear in root name j6ko02021 for the **crj** combined observation. GAIN = 2 and GAIN = 4 both used 8x12 seconds via CR-SPLITs and are in root names j6ko02071 and j6ko02061 respectively. The analyses were performed as with the HRC 9560 data discussed above, and in each case the same 16 stars that are unsaturated at GAIN = 1 were used. The resulting ratios of counts relative to the GAIN = 1 standard are 1.0074 +/- 0.0014 and 0.9986 +/- 0.0015 for GAINs 2 and 4 respectively.

The GO-9443 data taken for geometric distortion definition purposes is centered on the core of 47 Tuc, and is taken full frame, therefore a much larger number of stars on each quadrant are available than via the 9560 data. Here the relevant observations are both in F475W and are taken without CR-SPLITs. The 60 second exposure at GAIN = 1 is j6ll01xzq_flt.fits and the 150 second exposure at GAIN = 2 is j6ll01yeq_flt.fits. I use stars that have peak counts between 18,400 e- and 29,000 e- in the 60 second exposure that will remain unsaturated at the longer exposure. Sky levels for both exposures are evaluated using the same pixel set and are subtracted globally. Extraction with an aperture of radius 6 pixels for 1854 stars results in counts at GAIN = 2 compared to GAIN = 1 of 1.0078 +/- 0.0001. This result is shown in Figure 2 with stars between about 0.5 and 0.9 on the x-axis contributing to the relative gain determination. The 9443 data support evaluating this ratio on a quadrant-by-quadrant basis, the total spread in resulting values was less than 0.1% and it is best to assume the same correction factor applies to all amplifiers.

The more accurate result from the 9443 data may be applied to gain values of current (new) to arrive at: AMP A 2.018 (2.002), AMP B 1.960 (1.945), AMP C 2.044 (2.028), and AMP D 2.010 (1.994). Although only directly measured for AMP A, I assume that the ratio of GAIN = 4 to GAIN = 1 from 9560 data holds for all the AMPs, dividing values by 0.9986 provides current (new) results of: AMP A 4.005 (4.011), AMP B 3.897 (3.902), AMP C 4.068 (4.074), and AMP D 3.990 (3.996) for this available-but-unsupported gain.

**Figure 2:** The x-axis shows the expected peak counts in the long 150 second WFC exposure based on scaling up from unsaturated stars in a 60 second image, and then ratioing to the spatially dependent CCD full well depth. Values in excess of 1.0 are saturated stars in the long exposure. The ordinate shows the ratio of aperture-summed counts in the long exposure relative to the short with the relative exposure time taken out, deviations from unity show relative error in the assumed gain values. The horizontal line at 1.0078 shows the adopted correction factor for GAIN=2 relative to the default GAIN=1 value.




## Full Well Depths

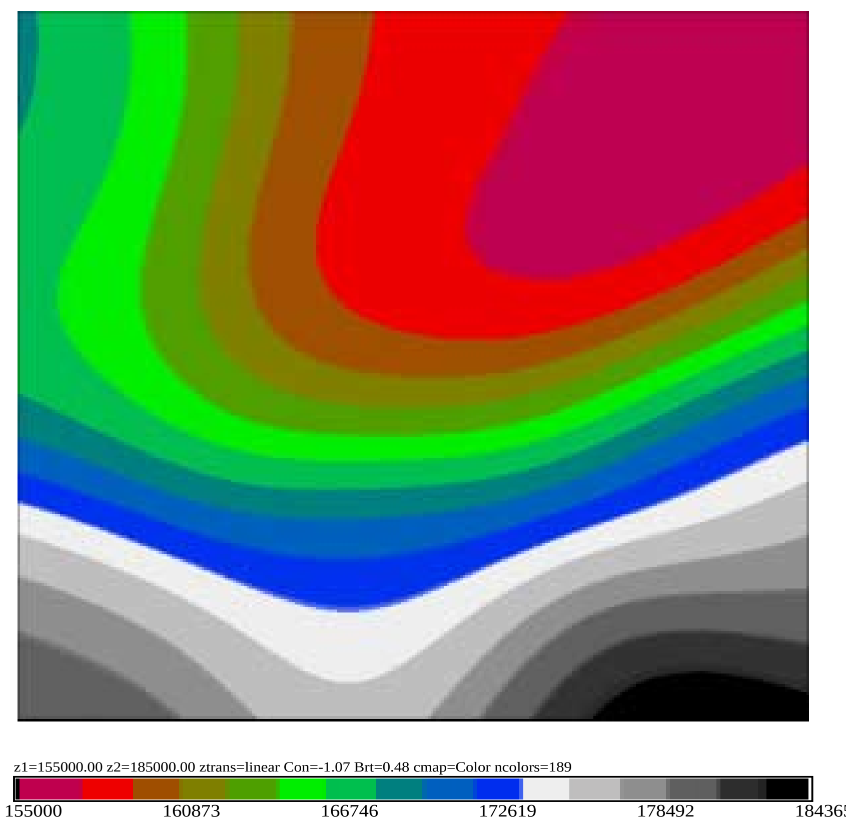
Conceptually, full well depths can be derived by analyzing images of a rich star field taken at two significantly different exposure times, identifying bright, but still unsaturated stars in the short exposure image, calculating which stars will saturate in the longer exposure and then simply recording the peak value reached for each star in electrons (using a gain that samples the full well depth of course). In practice there is one minor complication that must be taken into account. The number of electrons recorded in a saturated pixel depends weakly on the level of over-saturation. An example: at an exposure level where a star is expected to exceed saturation in the central pixel by a factor of about x1.5 the central intensity in a specific case reaches 81,972 e-, the same star in a longer exposure at a factor of 36 over-saturation reaches 89,987 e-. The desired quantity is the value in e- at which saturation just sets in, therefore a correction factor needs to be applied for any given saturated star. An appropriate correction function may be worked up as a function of the number of pixels that have been bled into. For the WFC I adopted a piecewise linear representation starting at 1.0 at one saturated pixel, increasing to 1.05 for 10 saturated pixels, 1.07 at 20, 1.08 at 50, up to 1.09 at 100 saturated pixels. For the HRC comparable correction factors at 1.033 at 10, 1.046 at 20, 1.053 at 50 up to 1.06 at 100 saturated pixels were used.

Since the full well depth may vary over the CCDs, it is desired to have a rich star field observed at a gain that samples the full well depth, and for which a large number of stars saturate.

***High Resolution Camera.***

For the HRC the GO-9443 observations discussed in the previous section work well having 75 saturated stars uniformly distributed over the CCD. Inspection of the derived full well depths as a function of position showed excellent consistency star-to-star with clear evidence of a large scale variation of about 20% over the CCD, the smallest full well depth values are at about 155,000 e- and the largest at about 185,000 e-, with 165,000 e- representing a rough estimate at an area weighted average value. The variation of full well depth after smoothing over spatial scales about one-third the linear CCD size are shown in Figure 3.

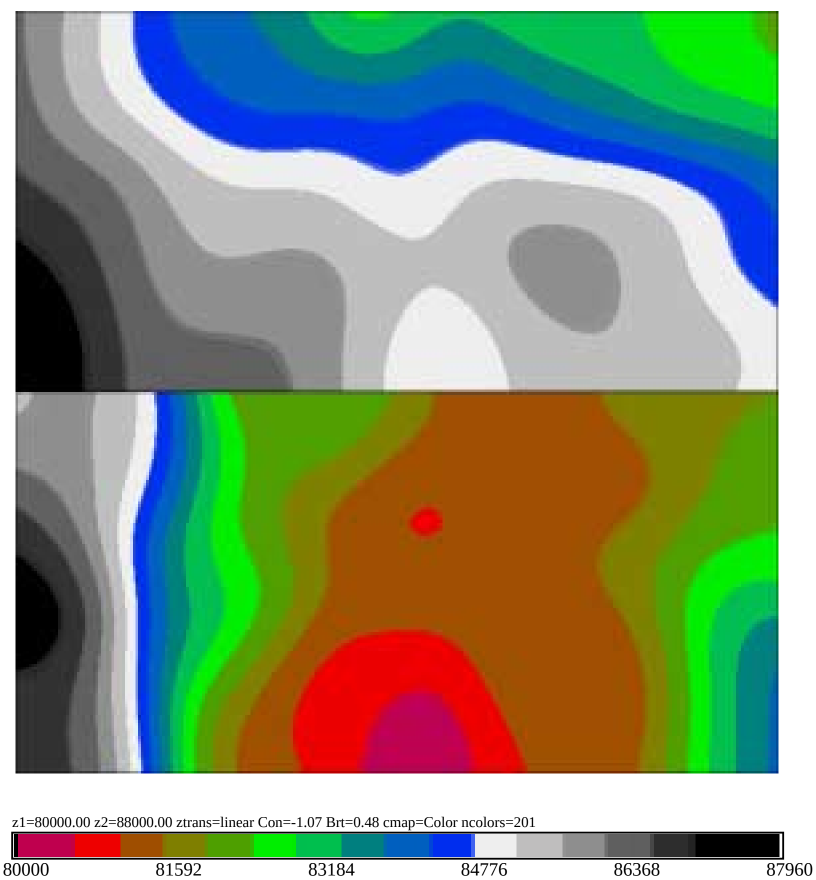
**Figure 3:** This image shows the variation of full well depth in electrons over the full field of view of the HRC after smoothing over values for 75 stars. A large-scale variation of 20% is visible.



***Wide Field Camera.***

The best data set identified for this follows from the PSF calibration images taken as part of the GO-9433 program using the L-flat field region in 47 Tuc. The 10 second exposures are useful for finding stars that will then saturate in the longer 340 second exposures. After combining results for the two epochs a quite adequate 935 stars uniformly distributed over WFC1 and WFC2 are available for definition of the spatially dependent full well depth. The smoothed version shown in Figure 4 utilizes averaging over spatial scales of about 600 pixels, but stars located near the boundary between the two CCDs are not included in the solution for the other CCD, thus allowing for a step function across the physically distinct devices. As with the HRC there is a real and significant large scale variation of the full well depth on the WFC CCDs. The variation over the WFC CCDs is from about 80,000 e- to 88,000 e- with a typical value of about 84,000 e-. There is a significant offset between the two CCDs, and no apparent correlation with the CCD thickness as reported in Krist 2003.

**Figure 4:** This image shows the variation of full well depth in electrons over the full field of view of the WFC after smoothing over values for 935 stars, the two CCDs have been concatonated with WFC2 on the bottom. A large-scale variation of 10% is visible.



## Linearity at Low to Moderate Intensity.

The results shown earlier in Figures 1 and 2 suggest that linearity holds well at moderate intensity levels for both cameras. The challenge here will be to test this result at low intensity levels where the noise level on individual measurements will be large compared to the level of sensitivity desired, requiring that results be averaged over many individual sources, and as many repeated exposures as possible.

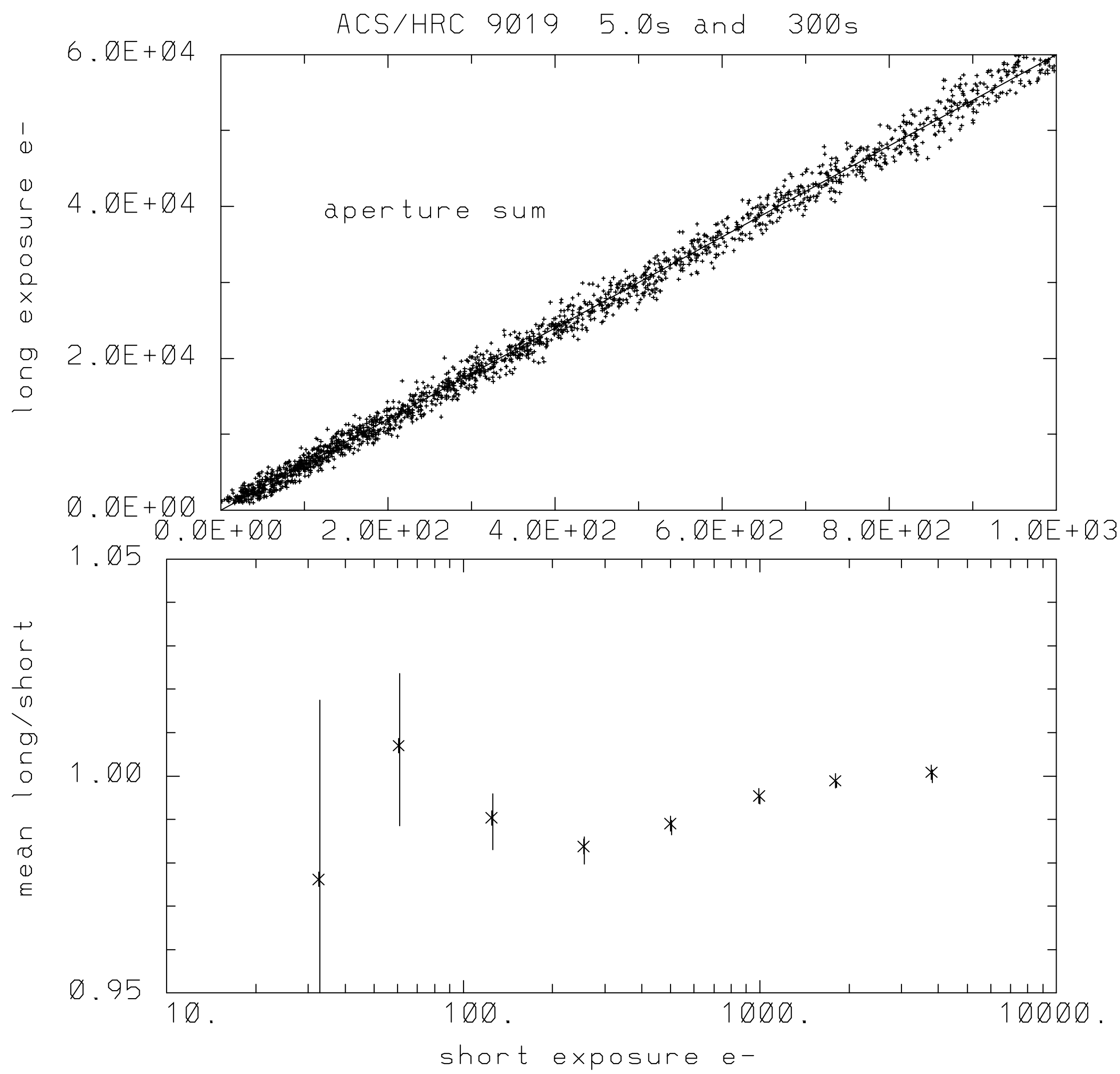
### *High Resolution Camera.*

The observations obtained April 13, 2002 as part of CAL/9019 will be used to quantify linearity at low to moderate signal levels. At this early date the analyses are not complicated from the existence of significant CTE losses, and such will be separately searched for via y-dependence of any apparent non-linearity. The particular data analyzed are CR-SPLIT pairs at total integrations of 10 and 600 seconds for j8bt06011_crj.fits and j8bt06031_crj.fits respectively. DAOFIND was run on the long exposure case to identify stars to be analyzed further in both the long and short exposures. The resulting star list was carefully trimmed to retain only stars that are unsaturated in the long exposure, had a count ratio within narrow bounds relative to an intermediate set of 60 second exposures (further guard against cosmic rays), and to lack problematic near neighbors. The final list consists of 3001 stars, the faintest of which in single short exposures will have peak count levels of only 5 e- and integrated over 9 pixels (total, not radius) a signal-to-noise of about unity. To allow analysis of results for such faint stars it is necessary to sum over many individual stars before conducting a comparison of counts between the long and short exposures. In Figure 5 the results are shown in two ways. The first is a simple plot of aperture sum values in the long exposures versus the same stars (alignment between exposures was good at the level of a few hundreths of a pixel) on the same pixels in the short exposure -- no deviations from linearity are evident. For a more sensitive test the second approach shows the results of summing counts over all stars within a defined magnitude range in the short and long cases separately, before then taking the ratio and normalizing to the relative exposure times.

A critical component of the analysis involves determining local sky for each star in the short and long exposures separately before subtracting, after experimentation it was determined that measuring the sky in the long exposure, and then simply scaling this down by the mean relative value of sky in the two cases, gave the most stable results. The small deviations seen from perfect linearity are not considered significant, although in a few cases the deviation is larger than a formal one sigma error. Uncertainties in the definition of sky, not included in the formal error bars, are sufficient to allow deviations comparable to those seen here. The data were also divided into two sets based on distance from the readout amplifier -- no significant differences were found suggesting that CTE losses at this early epoch are indeed small. By one year post-launch CTE losses are expected to be about 3% for the lower intensity bins (Riess 2003), thus dominating any intrinsic low-level nonlinearities.

The linearity of the HRC at low and moderate intensity levels, as evidenced by comparing stars observed with exposures differing by a factor of 60, appears to be excellent.

**Figure 5:** The upper panel shows aperture sums over 9 pixels for all stars used over a range emphasizing results at low to moderate count levels. The plotted line has a slope set by the relative exposure time. In the lower panel the ratio of counts in ensembles of stars divided into factor of two intensity bins, and further normalized by the relative exposure time are shown. One sigma error bars are derived based on the ensemble signal to noise of the short exposure case. The lowest bin has 81 stars, with typical values of 400 stars per bin above this.

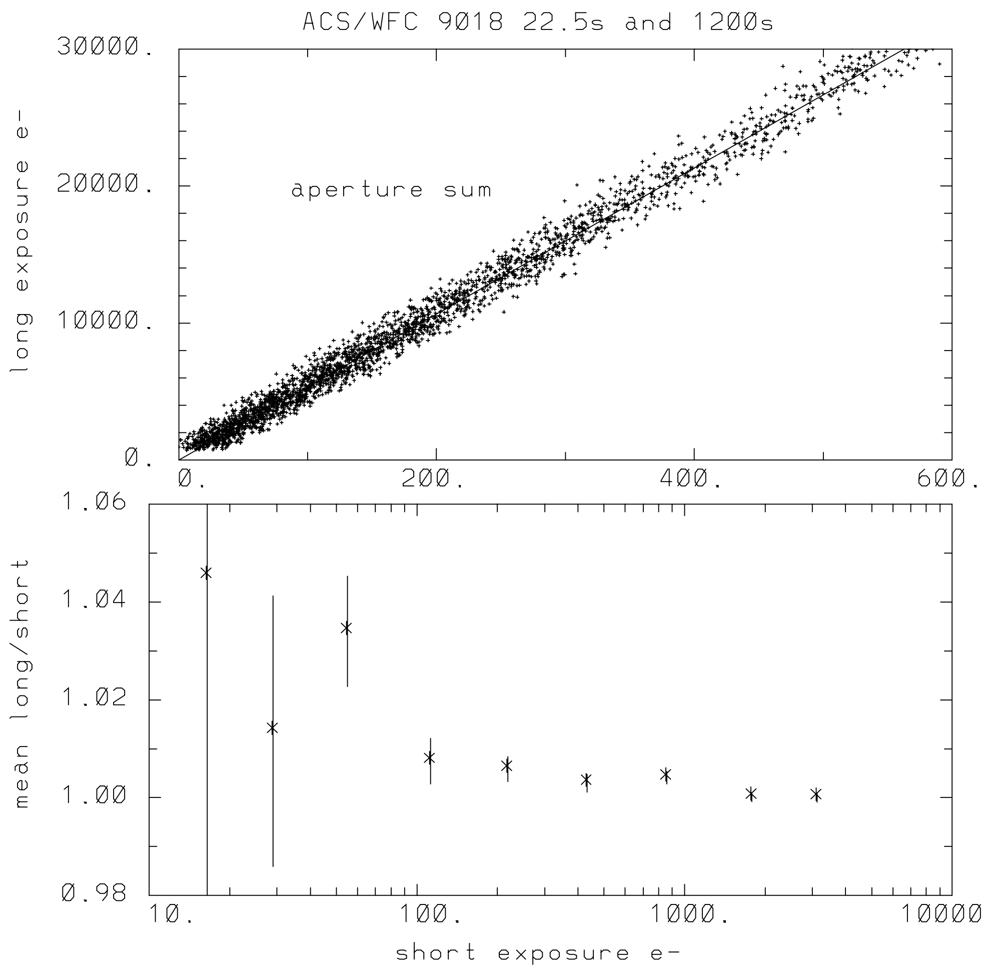


***Wide Field Camera.***

To test for possible non-linearity at low intensity level I have utilized CR-SPLIT pairs with exposure times of 22.5 seconds from CAL/9018 coupled with a much longer single exposure. All exposures discussed here are with F606W. At GAIN = 1 the comparison is with j8c061021_crj.fits and the 1200 second j8c061vnq_flt.fits, each from April 19, 2002. At GAIN = 2 the short exposure is j8c0c1011_crj.fits which can be compared with j8c0a2dfq_flt.fits at 690 seconds. DAOFIND is executed on the 1200 second exposure to identify a broad range of unsaturated stars, including a substantial sample that would not be individually recognizable in the short exposures taken at the same pointing. Since the exposure time ratios of 53.3 at GAIN = 1 and 30.7 at GAIN =2 are too large to support robust elimination of cosmic rays that may be present in the longer exposures, I have relied on comparison of the 1200 and 690 second exposures, requiring relative count levels to remain within a narrow range, in order to discard stars that may have been effected by cosmic rays. In order to arrive at a pristine list of stars any are also dropped that (a) are within a few pixels of a bleeding trail from a saturated star, (b) had cosmic rays eliminated within either of the CR-SPLIT pairs, (c) reach saturation in the 1200 second exposure, or (d) have non-zero data quality flags within the aperture to be used. After these scrubs a total of 3901 stars remained spanning summed count levels of about 200,000 on the bright end to about 900 e- within a 9 pixel (total, not radius) aperture used. At an exposure time ratio of 53.3 for the GAIN = 1 case this implies use of images with expected total counts of only 17 e- (which over 9 pixels would have a signal to noise of almost exactly 1.0), the central pixel in the short exposure for the faintest stars used have only 5 e-. Clearly, on a star-by-star basis the ratio of counts in the long to the short exposures, normalized by the relative exposure time, will be poorly constrained (the short exposure sums can even be negative given expected noise fluctuations). In making the comparison of counts in long and short exposures I therefore perform sums over 9 pixels, and over all of the stars within an intensity range before taking the ratio of long to short to search for non-linearity.

As shown in Figure 6 counts within small apertures suggest excellent linearity down to quite low exposure levels of about 5 e- in the central pixel for stellar sources, i.e., down to a level where individual stars cannot be recognized in single exposures. Although the CTE is expected to yield minor losses at this early, April 19, 2002 epoch it is still worth evaluating what would be expected based upon the later CTE measures summarized in ISR 2003-09. The lowest three bins in Figure 6 would be expected to show effects at 3.0%, 2.0% and 1.3% respectively, values that are comparable to those measured. These data were also divided up into two sets, the first for stars on each WFC chip within 1024 rows of the amplifiers, and the second for those at greater than 1024 parallel transfers from the readout amplifiers. The impact of CTE should be a factor of three larger (1536 transfers on average for the second, compared to 512 for the first) for the second case. A comparison of values for the lowest intensities studied here did not show any significant differences between the two cases suggesting that CTE impacts were no larger than, or even smaller than those assumed by the linear relation in time given in ISR 2003-09 (Riess 2003). By contrast at the approximately one year after launch observations used in ISR 2003-09 the CTE impact (at middle of CCDs) at the three lowest intensity levels in Figure 6 are at 24, 16, and 10.3% respectively. Thus, any intrinsic non-linearities that may exist at low intensity levels are small compared to the normal losses expected from CTE growth after ACS had been on orbit for only a few months. Within the mutual error bars results for the GAIN = 2 comparisons (22.5 and 690 seconds, three weeks after the data shown in Figure 6) are entirely consistent -- the low-level linearity of the WFC channel is obviously excellent.

**Figure 6:** The upper panel shows simple aperture sums for the long and short exposures for all stars of low-to-moderate intensity, the line has a slope set by the relative exposure times. The lower panel shows ratio of counts summed over all stars within intensity bins (in factor of two steps) for the 1200 second to mean 22.5 second exposures after normalization to the relative exposure time. To account for minor encirled energy differences for the very small 9 pixel (total, not radius) apertures used all points have been normalized by 1.006, the initial value for the brightest bin. The error bars show plus/minus one sigma deviations based on the total signal to noise of the short exposure sums. The number of stars per bin is typically about 400, although the lowest bin contains only 33 stars.



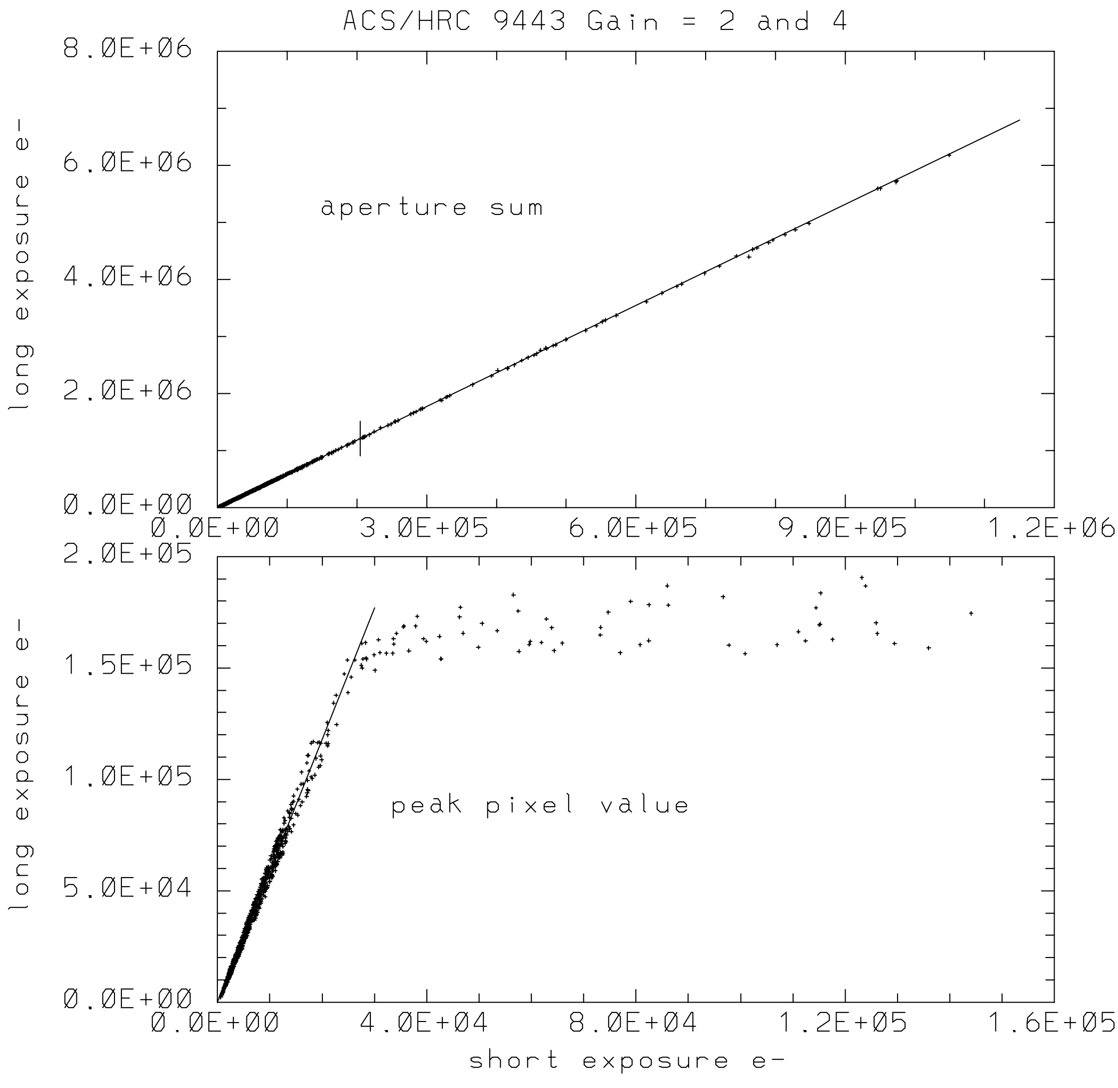
## Linearity Beyond Saturation.

Here I explore the extent to which accurate photometry can be extracted for point sources in which one or more pixels have exceeded the physical full well depth. I consider only the case of GAIN = 4 for the HRC and GAIN = 2 for the WFC, which provide direct sampling of the count levels independent of whether saturation has occurred. Ideal data for these tests consist of multiple exposures taken back-to-back on a moderate-to-rich star field with a broad range of exposure times resulting in both unsaturated and saturated data on many stars.

### *High Resolution Camera.*

The data from GO-9443 previously analyzed to derive the accurate GAIN = 4 value relative to the GAIN = 2 standard are useful here as well. These data consisted of 2x60s at GAIN = 2 followed by a 350s exposure in the same filter at GAIN = 4. The cross-calibration of the gains utilized stars with central intensity peaks of 10,000 to 25,000 e- in the short exposures which would remain unsaturated in the longer exposure. Since the HRC maximum full well depth value is about 185,000 e-, any stars with peaks above 32,000 e- in the short exposure are assured of saturating in the longer exposure. (With minimum full well depth of 155,000 e- some stars with peaks at 26,500 e- will saturate.) Since GAIN = 2 samples to about 143,000 e- measurements in the longer exposure will provide tests on over-saturations of up to a factor of five. The results shown earlier in Figure 1 showed that linearity was maintained to levels of up to 5 times saturation. Figure 7 illustrates this more directly, in the lower panel peak values in the long exposure are plotted against the same from the short exposure. Over the expected linear domain points fall within a narrow cone centered on a line that has a slope equal to the exposure time ratio (deviations from lying perfectly along the line here result primarily from a 0.1 pixel offset between the images leading to different relative fractions of light falling on the central pixel), while above this the values in the long exposure “saturate” as expected. The upper panel of Figure 5 shows the same stars but now using identical extraction apertures in the two exposures, the vertical tick mark near 205,000 e- on the x-axis flags stars below which the central pixel remained unsaturated, above which the central pixel experienced saturation. In the aperture sum data there is no difference in the long exposure photometric quality between stars that saturate, even up to a factor of 5, and those that do not. Within the domain sampled here the accuracy of saturated star photometry is much better than 1%.

**Figure 7:** The lower panel shows peak pixel values for many stars observed for 350 seconds (long) and 60 seconds (short) with the HRC; over the range for which stars are unsaturated in both exposures there is a linear relation with slope equal to exposure time ratio. Brighter stars in the long exposure saturate at values near the full well depth. The upper panel shows the same stars using photometry sums from identical apertures in both exposures, stars above the vertical mark near 205,000 on the x-axis separates stars that are saturated in the long exposure. The photometric response when summing over saturated pixels that have been bled into remains perfectly linear far beyond saturation of the central pixel at GAIN=4.

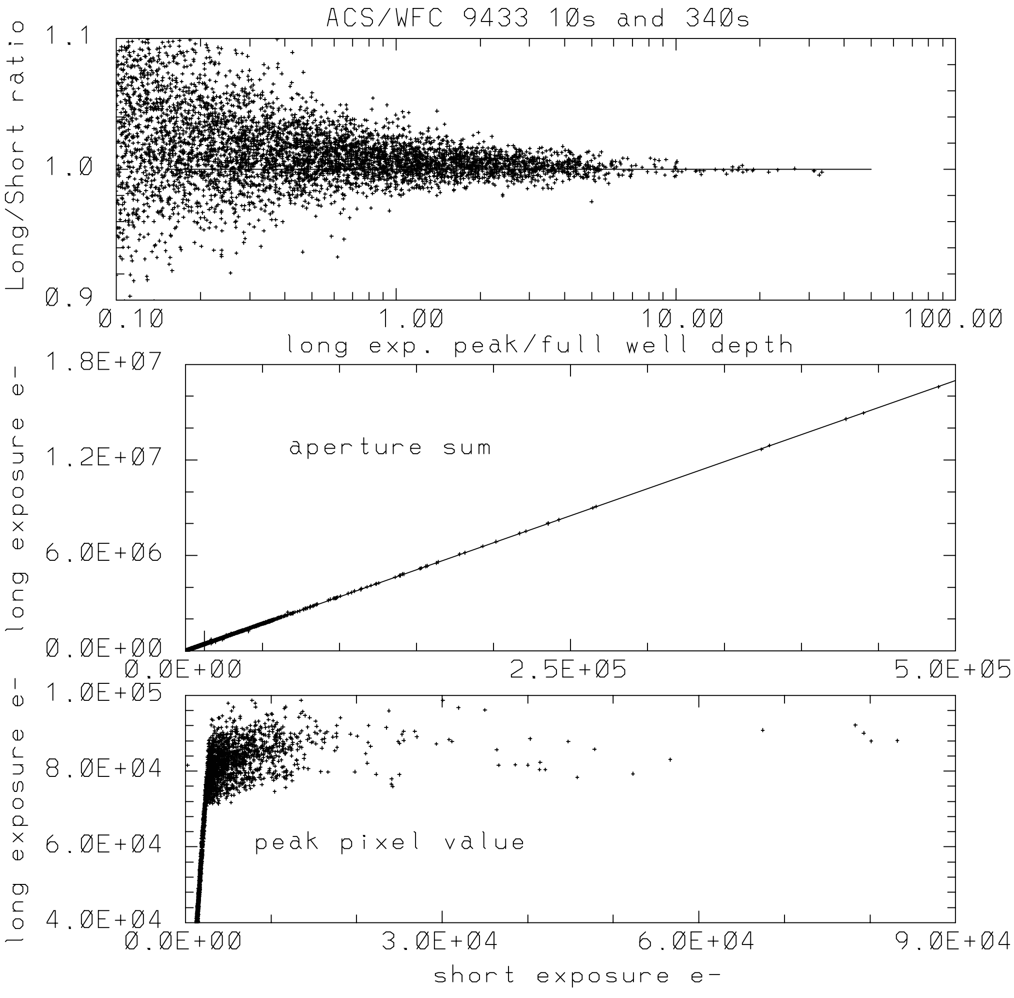


***Wide Field Camera.***

The results for WFC shown in Figure 2 from GO-9443 data also demonstrated linearity beyond saturation. At least up to the factor of 2 over-saturation sampled here linearity to much better than 1% holds for WFC data.

In order to extend these results to higher levels of over-saturation I have used the GO-9433 data for which 10 second and 340 second exposures were obtained back-to-back at GAIN=2 allowing for checks at up to a factor of 30 over-saturation. Figure 8 shows these results. The 1,414 stars with long-exposure, over-saturation of 1.0 to 10.0 have counts of 1.009 +/- 0.009 relative to the unsaturated, short exposure photometry. There is evidence for a very weak non-linearity, the 32 stars with over-saturation > 10.0 show relative counts of 0.999 +/- 0.002. Thus, over a range of nearly 4 magnitudes beyond saturation, photometry remains linear to < 1%.

**Figure 8:** The lower panel shows peak pixel values for many stars observed for 340 seconds (long) and 10 seconds (short) with the WFC; over the range for which stars are unsaturated in both exposures there is a linear relation with slope equal to the exposure time ratio. Brighter stars in the long exposure saturate at values near the full well depth. The middle panel shows the same stars using photometry sums from identical apertures in both exposures, stars above the vertical mark near 12,350 on the x-axis separates stars that are saturated in the long exposure The upper panel shows the ratio of long to short aperture sums normalized by the relative exposure time plotted against the degree of over-saturation in the central pixel of the long exposure. The plotted line in each panel represents perfect linearity, rather than fits to the data. The photometric response when summing over saturated pixels that have been bled into remains perfectly linear far beyond saturation of the central pixel at GAIN=2.




All of the above results are based upon comparisons of **flt** images. The conservation of flux property of drizzle leads to equally good results for linearity beyond saturation comparing long and short **drz** images. An analysis of the drizzled data sets corresponding to Figure 8 show equally impressive results.

## Summary.

Relative to the references of GAIN=2 on the HRC and GAIN=1 on the WFC, the GAIN=4 and GAIN=2 values have been adjusted by 1.27% and 0.78% respectively; these determinations are secure at > 10 $\sigma$ . Maps of the CCD full well depths have been generated that show spatial variations in excess of 10% for both cameras.

All of the ACS CCDs show that charge is conserved to a high degree of accuracy as the central pixel of point sources reaches and exceeds nominal saturation. When operated at GAIN=4 for the HRC, or GAIN=2 for the WFC, both of which provide full sampling of the full well depth, photometry on isolated sources can be easily recovered from saturated images simply by assuring that the aperture extraction includes all of the pixels bled into during saturation (and nearest neighbors to allow for charge diffusion).

Both CCD cameras show excellent linearity with no evidence for deviations at either low or high signal levels (even to factors of several beyond saturation) that would need to be taken into account to routinely support photometry to better than 1%.

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