

Stability and Accuracy of HRC and WFC Shutters

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ABSTRACT

Calibration observations (9662) have been used to quantify precise exposure time values, stability and shading effects down to the shortest allowed exposures (0.1s HRC, 0.5s WFC). A few of the shortest exposure times differ by up to 4% from nominal values, and we recommend for these cases that CALACS, or its reference files be changed to use the measured exposure times. In general no significant differences were found between the exposures controlled with the A and B shutters, with the possible exception of WFC exposures of 0.7 -- 2.0 s, for which differences of order 1% may sometimes occur. No shutter shading effects of significance were found for either camera. These observations used the CLEAR filter thus providing calibration of PSF quality in the resulting out-of-focus images; degradation is very minor for the HRC, but significant for the WFC.

Introduction

A small subset of GO/GTO science programs utilize short exposure times, with a more significant fraction of such in the general calibration program given the need to observe relatively bright targets. Shutter management varies for the shortest exposures, e.g. at 0.5s for WFC it is a continuous motion, 0.6s is not allowed and 0.7s begins the standard mode of operation. Similar differences exist for the shortest HRC options.

Ground-based testing is discussed by Martel, Hartig and Sirianni (2001) and should be referred to for background on operation of the shutters. The ground results using time-variable flat-field sources were suggestive of deviations (actual versus nominal exposure times) to ~1% for short WFC and HRC exposures, with exception of the HRC at 0.1s (the case for which we find a 4% difference).

With a goal of supporting photometry to better than 1% in general for ACS CCD observations, knowledge of relative shutter-open times to significantly better than 1% is needed.

Observations

In order to reach Poisson-limited precision levels approaching 0.1% in the shortest available exposure times, while keeping the same stars unsaturated in longer control exposures it is necessary to observe a rich star field through a broad filter. For this program the core of 47 Tucanae has been observed through the CLEAR filter (actually this is without a filter) yielding throughputs a factor of 2-3 times higher than with F606W.

This calibration could in principle be attempted using the onboard tungsten calibration lamp, but concerns over its temporal stability at well under 1% argued for use of a large ensemble of stars.

The general procedure has been to obtain observations for both HRC and WFC with exposure times including the shortest allowed, several at 50 times the shortest, and at a sampling of other short exposure times. The longest exposures (5.0s HRC, 25.0s WFC) are used to define the standard with assumed negligible errors on the absolute exposure times. The ratio of count rates at short and long exposures then directly establishes relative errors on values at the short exposure times.

Three distinct sets of exposures were obtained:

(1) HRC. Full frame images were taken at 0.1, 0.2, 0.3, 0.4, 0.5, 1.0, 2.0 and 5.0 seconds in the CLEAR filter. (Two 1.0s F606W exposures also were taken to allow relative PSF definition.) These data support both absolute exposure time quantification and testing for shading (variation of exposure time over the field) in shutter A and B control separately. Eight exposures were taken at 0.1s, four at all other times except 1.0s which were taken in pairs separating the other sets (allowing for tracking of any temporal drifts).

(2) WFC 1024 X 1024 subarrays. Images were taken at 0.5, 0.7, 0.8, 1.0, 2.0, 10.0 and 25.0 s in CLEAR (plus 2 at 2.0s in F606W) to establish the accuracy of short exposure times. Eight exposures were taken at 0.5s, four for all the others except at 1.0s for which 14 were acquired dispersed in time.

(3) WFC full frame. Two exposures each at 0.5s, 1.0s and 25.0s in the CLEAR filter were obtained to support minimal testing under A and B shutter control for shading.

The full 9662 data set consists of 48 HRC, 44 WFC subarray and 6 WFC full frame exposures acquired September 23, 2002 in a 2.5 orbit block of CVZ time. GAIN = 2 was used for both HRC and WFC.

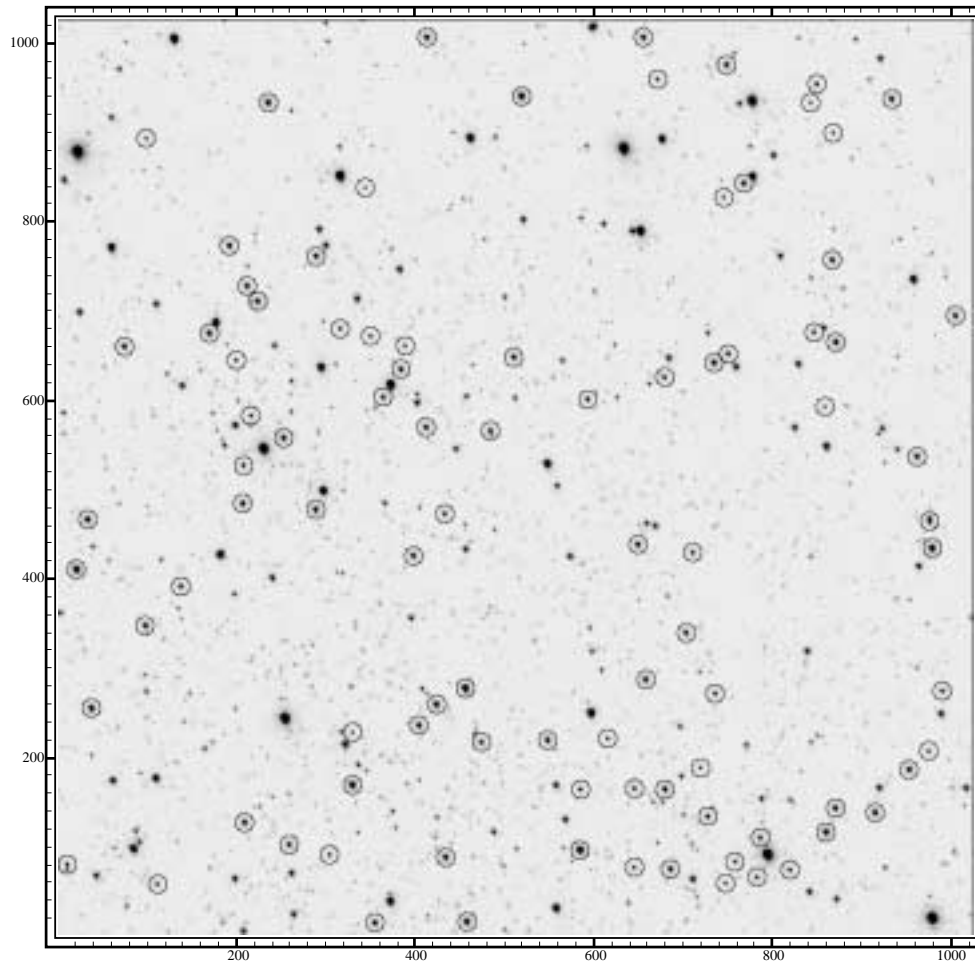
Analysis Quantifying Actual Exposure Times

Initial analysis of pipeline products for the CLEAR exposures indicated spurious data values in the **flt** files, e.g. saturation as indicated by the highest e- values was not close to expected values for either the HRC or WFC. It was found that the CLEAR flats in use dated from early pre-launch times, not only were the normalizations not close to unity, but features indicated a likely heritage to CCDs not used for flight. Following discussion with Ralph Bohlin and Jennifer Mack it was decided that CLEAR filter LP flats would be generated as averages of the pipeline flats for F475W, F555W and F775W which span the optical. (F606W and F814W were avoided, since these show significant filter dust motes.) All further analyses have used the **flt** files from the archive with appropriate CLEAR flats now used (HRC: n2d1344mj_pfl.fits, WFC: n3v0946oj_pfl.fits as generated by Jennifer Mack). (A single WFC CLEAR exposure has been added to CAL/9656, the standard L-flat field; this and the current HRC images would allow a verification of L-flat quality -- left as a low-priority future task.)

High Resolution Camera.

Figure 1 shows a 1.0s CLEAR exposure. Stars are selected for analysis to: 1) not reach saturation (A/D at GAIN = 2 of about 130,000 e-) in the longest (5.0s) exposures, 2) be within a factor of 10 in brightness on the faint end, and 3) have 7 pixel radius apertures that avoid saturation trails in the long exposures and bad pixels (other than a few slightly hot) in general. The 93 stars used on the HRC provide a total count rate of 8.9×10^6 e-/s. At the shortest exposure time of 0.1s this rich star field supports frame-to-frame relative exposure time measurements to 0.11%.

Figure 1: HRC CLEAR exposure of 1.0 s with stars used for shutter testing marked by



open circles. The field is the core of 47 Tucanae.

Centroiding measurements across the full HRC data set showed relative motions of ≤ 0.2 pixels thus allowing the same 7 pixel radius aperture on each star to be used throughout. Values for sky are computed using sigma clipping as applied to pixels over the full frame that are well off the stars and then sky is subtracted globally on each frame. Problematic (e.g. intrinsic variables) stars were eliminated by requiring that the *rms* over the 14 exposures at 1.0s spaced throughout the sequence remain close to the Poisson limit based on mean counts.

Cosmic rays are controlled for by rejecting individual star contributions that exceed 3σ (based on Poisson noise) above the mean. Control values of electrons/sec for each

star are formed as the sigma-clipped mean of the four exposures (A and B shutter control combined).

With units throughout in e-/s the basic analysis product is simply to evaluate the rate summed over all stars in the target case and ratio this to the control. Values deviating on the high(low) side would indicate actual exposure times multiplicatively higher(lower) than the nominal value assumed by CALACS. Separated by SHUTRPOS = A or B keyword values this allows testing for differences based on which shutter side controlled the exposure. Evaluated frame-to-frame this provides a measure of stability. The ratios analyzed for spatial dependence yield shading deviations.

Table 1 shows the relative exposure time ratios for the HRC as averages of all exposures (A and B shutters) using 5.0s exposures as the standard.

Table 1. HRC Exposure Times.

| Nominal(s) | Ratio | St. Error | Actual Texp |
|------------|--------|-----------|-------------|
| 0.1 | 1.0410 | 0.0009 | 0.1041 |
| 0.2 | 1.0042 | 0.0007 | 0.2008 |
| 0.3 | 1.0028 | 0.0005 | 0.3008 |
| 0.4 | 1.0029 | 0.0004 | 0.4012 |
| 0.5 | 1.0018 | 0.0005 | 0.5009 |
| 1.0 | 1.0027 | 0.0002 | 1.0027 |
| 2.0 | 1.0009 | 0.0002 | 2.0018 |

The Standard Error represents the formal statistical error on the sample mean of the ratio and does not allow for possible systematic effects. The Poisson noise per frame at 0.1s is 0.0011. The mean e- per pixel used in stellar apertures at 0.1s is 61, therefore to have sky subtraction contribute at less than the level of Poisson noise on direct counts requires determination of sky to ≤ 0.07 e- which is comparable to the fluctuation level of measured values. An additional factor that could add systematic noise arises from time-dependent focus changes, i.e. breathing, since this can lead to changes of flux within the apertures used. Affects from breathing can be tracked using the 1.0s exposures which were spread out uniformly in time. The implied corrections for the HRC are small at \pm one part per thousand and have been factored into the results in Table 1. If the CCD response is nonlinear, this would appear as an exposure time dependent effect for this experiment. The stars in use span a factor of 10 in brightness. Repeating the measures with either the bright or faint half of the stars showed no significant differences.

Stability of exposure times can be measured by evaluating frame-by-frame (not shown) values of the correction factor converted to time. HRC exposures show typical

frame-to-frame fluctuations in exposure time of 0.6 msec with largest deviations in repeated exposures at ~2 msec.

With allowance for statistical and possible residual systematic errors a realistic 1- σ error (on ratio) of 0.001 is reasonable for the HRC values. Only the 0.1s exposure time differs at a high level of significance from the nominal exposure time. At $t_{\text{exp}} = 0.1\text{s}$ the actual exposure time is 4.1% longer than this, and any frame-to-frame fluctuations on this are an order of magnitude smaller than the implied correction factor. At the longer exposure times the implied corrections are comparable in size to the (very small at ~0.6 msec) possible level of frame-to-frame intrinsic fluctuations.

Since the 0.1s exposure results from a continuous motion of the shutter, a change in effective exposure times implies a different velocity of rotation.

Any exposure time difference between use of A and B shutters is deemed insignificant, e.g. at 0.1s the implied actuals are 0.1041 and 0.1042 respectively.

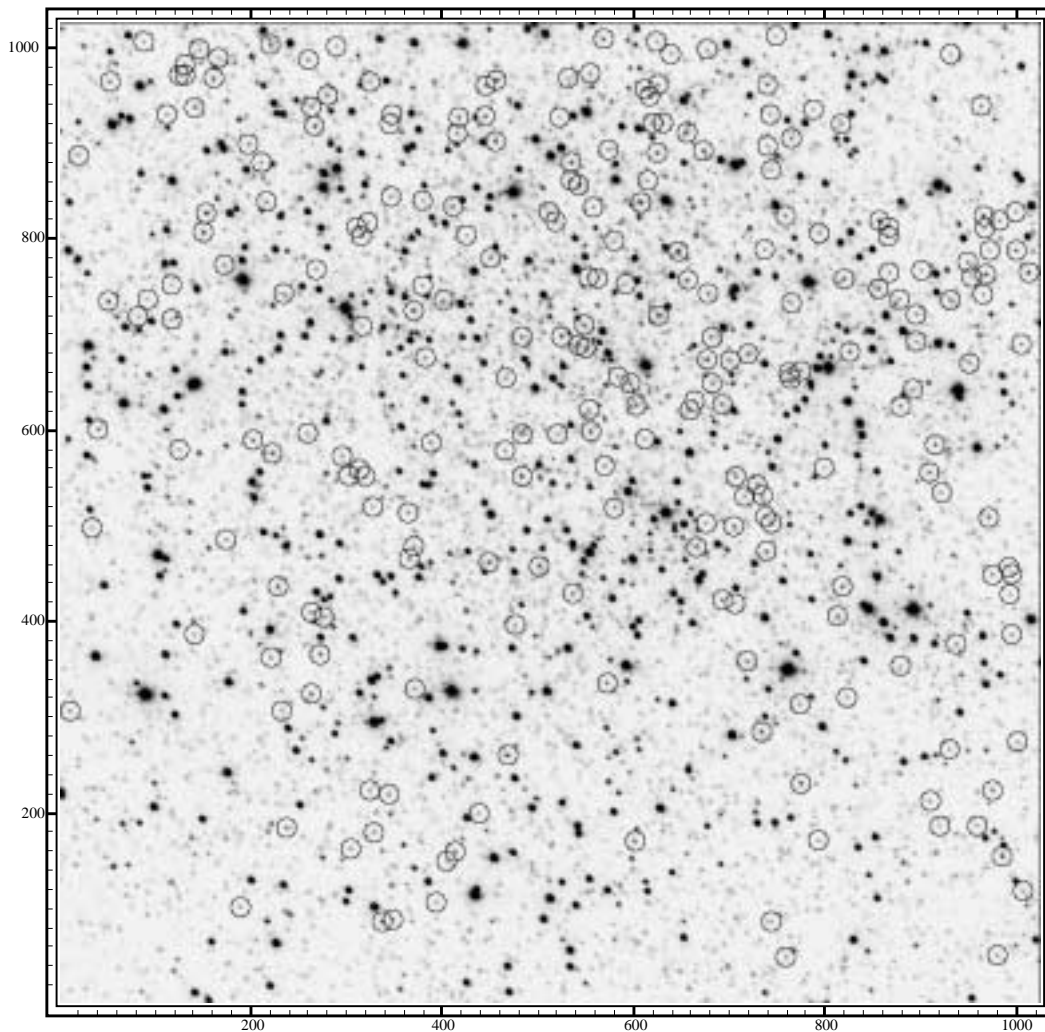
A reasonable interpretation is that neither the ground or on-orbit tests detect significant deviations from nominal for exposures other than 0.1s. At 0.1s the results here are in good agreement with the ground results lending confidence in this result.

A search for shutter shading has been made at each exposure time, and for A and B shutter control separately by fitting a plane to relative deviations as a function of x,y over the detector. No deviations (center-to-corner) above 0.4% relative were found for any exposure time. No evidence for needing a shading correction has been found.

Wide Field Camera.

Figure 2 shows a 1.0s CLEAR exposure using a 1024X1024 subarray on WFC1. Stars are selected for analysis to: 1) not reach saturation (full well of ~85,000 e-) in the longest (25.0s) exposures, 2) be within a factor of 10 in brightness on the faint end, and 3) have 7 pixel radius apertures that avoid saturation trails in the long exposures and bad pixels in general (other than a few slightly hot). The 242 stars used on the WFC provide a total count rate of 8.3×10^6 e-/s. At the shortest exposure time of 0.5s frame-to-frame relative exposure times to 0.05% can be assessed based on the Poisson noise alone.

Figure 2: WFC CLEAR exposure of 1.0 s using 1024X1024 subarray with the 242 stars used marked with circles.



As with the HRC, centroiding measurements across the full WFC data set showed relative motions of ≤ 0.2 pixels, thus allowing the same 7 pixel radius aperture to be used throughout on each star. Corrections for sky, avoidance of variable stars and cosmic rays were handled as described for the HRC.

As will be discussed further in the next section, the WFC PSF resulting from filterless (CLEAR) exposures is significantly broader as a result of the lack of focus. The lack of focus makes the images particularly sensitive to breathing; casual inspection of 1.0s images from early in the series to late show that substantial variations of the PSF result. Consequently, even though the 7 pixel radius apertures in use extend well beyond the PSF core, there is a large temporal dependence in the apparent duration of the 1.0s exposures which were interspersed in pairs throughout the observing period. The sign of the effect is

consistent -- as the PSF broadens the amount of flux in the aperture drops and the naively interpreted exposure time drops as well. What had been a second order effect for the HRC becomes primary for these WFC data. The relative change in time of encircled energy is defined by the interspersed 1.0s exposures, then this time dependent correction is applied before deriving estimated count rates for other cases. The 8 exposures at 0.5s were split between beginning and end of the overall observing sequence, with correction for the breathing trend of nearly 1% (defined from the interspersed 1.0s exposures) the two sets are entirely consistent.

Given the sensitivity to breathing using a 7 pixel radius aperture, analyses were also performed using a 9 pixel radius on a smaller (137) number of more isolated stars. Breathing effects dropped in amplitude, but remained a significant factor.

Table 2 shows the relative exposure time ratios for the WFC (A and B shutters averaged) using 25.0s exposures as the control (these numbers are for the 9 pixel radius aperture analyses, results at 7 pixel radius were very similar).

Table 2. WFC Exposure Times.

| Nominal(s) | Ratio | Actual Texp |
|------------|--------|-------------|
| 0.5 | 1.0157 | 0.5079 |
| 0.7 | 0.9906 | 0.6934 |
| 0.8 | 0.9944 | 0.7955 |
| 1.0 | 0.9991 | 0.9991 |
| 2.0 | 1.0007 | 2.0014 |
| 10.0 | 1.0005 | 10.005 |

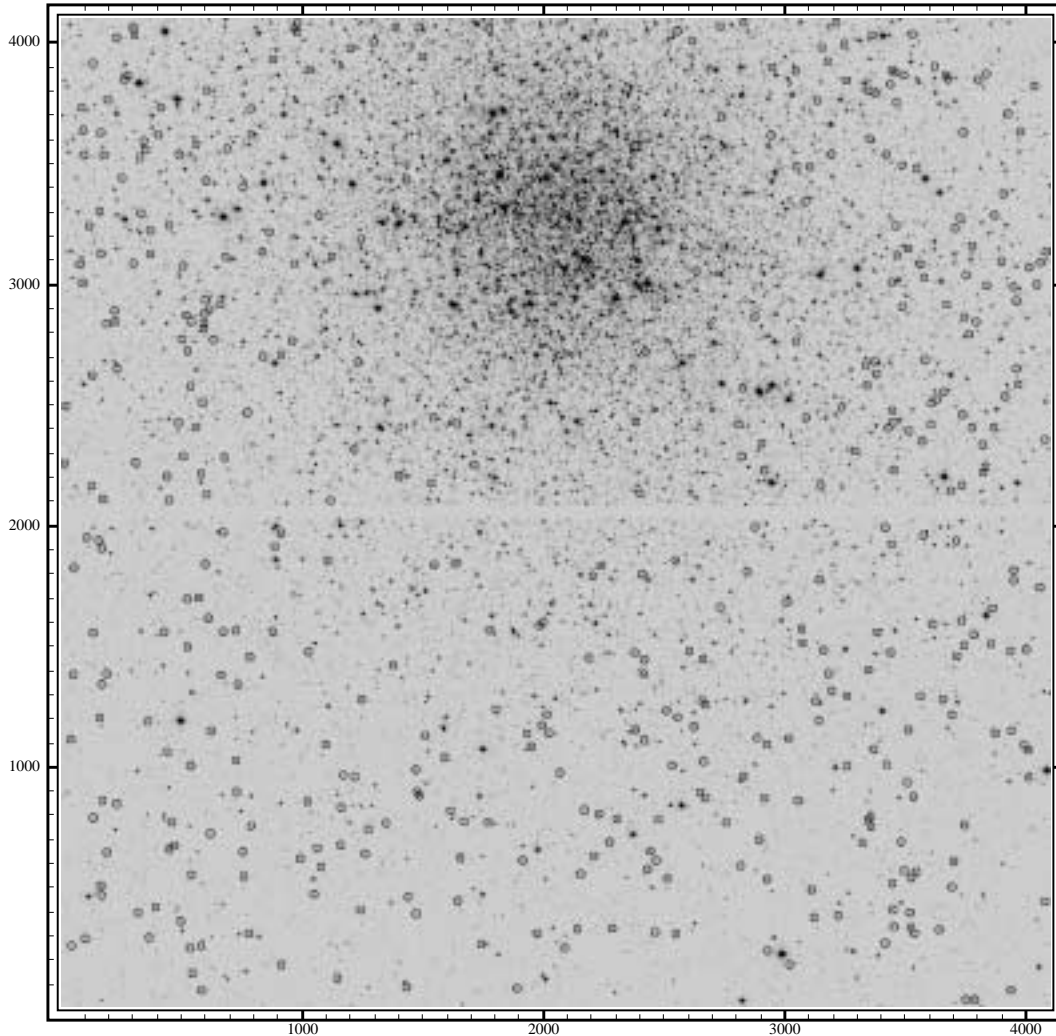
Errors on the ratios in this case are dominated by systematics of correcting for breathing induced changes for which a value of about 0.002 (additive to Ratio term) applies. Comparison with ground test results (Martel et al. 2001) shows both similarities and differences. In both cases the 0.7s exposure time shows the largest negative deviation and comes in ~1% low. In both studies 1.0s exposures are near nominal. But in the ground based test the 0.5s exposures are low by 0.5%, while the on-orbit data yield high by 1.5%. No explanation for the discrepancy at 0.5s is apparent -- the on-orbit measure securely suggests longer than nominal exposure times. The continuous motion 0.5s exposure result would be consistent with a slower rotational velocity in zero-g shutter operation.

Interpretation of the on-orbit WFC subarray data for stability, or A versus B shutter differences produces mixed results. The 6 exposures at 0.5s taken contiguously within a less than 10 minute span show a standard deviation corresponding to < 1 msec with any difference between exposure times split by A versus B also < 1 msec. A total of 7 A and B shutter pairs were taken at 1.0s, apparent differences between the A and B exposure times

range up to 13 and 14 msec in two cases. Where significant differences exist it is always the case that exposure times are shorter when terminated by the A shutter. No ready explanation has been found for these differences. An error on sky of 2.7 e- per pixel would be required to explain this, derived sky values are steady to an order of magnitude better than this. Guiding frame-to-frame appears to be good to a few hundredths of a pixel. (Jitter files are not available for the subarray exposures, but two guide stars were in use and jitter during the full frame exposures taken with the same guide stars showed nominal values with peak to peak offsets an order of magnitude away from sufficiency to explain the count rate offsets). The apparent exposure time offsets frame-to-frame cannot be explained as resulting from a few spurious stars (e.g. as affected by cosmic rays) skewing the results, similar offsets are seen in the median ratio of count rates. A record of shutter resolver positions is returned and available via the **spt** files; examination of the shutter position record throughout the sequence does not show large and consistent deviations associated with the 1.0s exposure pairs that showed apparent timing differences. Direct tests for PSF width seem to rule out breathing effects (nor would such be expected for back-to-back exposures). Exposure time variations > 10 msec ($>1\%$ at 1.0s) have not been ruled out, and lacking any better viable explanation seem the most likely interpretation, although in general frame-to-frame stability is much better than this.

Evaluation of WFC shading requires full frame images. Figure 3 shows a 4096X4096 image constructed by patching together the two extensions from **flt** processed data with an appropriate gap introduced. To facilitate analyses less sensitive to breathing a more restrictive algorithm was used for generation of the star list. In particular the target stars are required to be isolated -- no neighbors within 10 pixels to 4 magnitudes fainter. This has the effect of avoiding the cluster center. For analysis of the 433 stars retained apertures with a radius of 9 pixels are used. Two exposures were acquired at each of 0.5s, 1.0s and 25.0s to constrain shading. Intensities at 25.0s were averaged over A and B cases to provide the reference. For analysis of these full frame data, sky is evaluated for each star over an annulus from 10.5 - 15.0 pixels and subtracted locally from the aperture sum.

Figure 3: Full frame WFC 1.0 s CLEAR image with the 433 isolated stars used to test for shutter shading marked with circles.



Cosmic rays have been eliminated by comparing the paired exposures and applying logic similar to CALACS. Shading is tested for by fitting a plane to the ratio (to 25.0s as standard) of count rates over x,y to each short exposure separately. Evaluated center-to-edge shading gradients up to 0.5% are found at 0.5s and up to 0.2% at 1.0s. These results suggest that shading corrections are not necessary, even at the shortest exposure times available, to support the general goal of 1% relative photometry across the full field of view. Other constraints (flat fields, variation of PSF) are more likely to remain limiting factors for absolute photometric accuracy.

Auxiliary results.

Clear filter image quality.

Comparison exposures were obtained with F606W on both HRC and WFC to allow the CAL/9662 data to also serve as a characterization of PSF quality using the CLEAR filter. Figure 4 shows roughly 5X5 arcsecond fields in the core of 47 Tuc observed with the four permutations of camera and filter. The data shown in Figure 4 are from the **fit** files (still geometrically distorted) in order to best show PSF differences. Within a camera the data for F606W and CLEAR are shown at a common stretch, although in each case the exposure time in F606W was twice that in CLEAR. Summaries of key PSF differences are shown in Table 3.

Figure 4: A composite image showing the same $\sim 5 \times 5$ arcsecond region at the core of 47 Tuc as observed with the HRC and WFC each with the F606W and CLEAR filters. All subimages are from **fit** images; the WFC cases have used 2×2 pixel replication and rotation by 180 degrees to roughly match the HRC scale and orient for display.

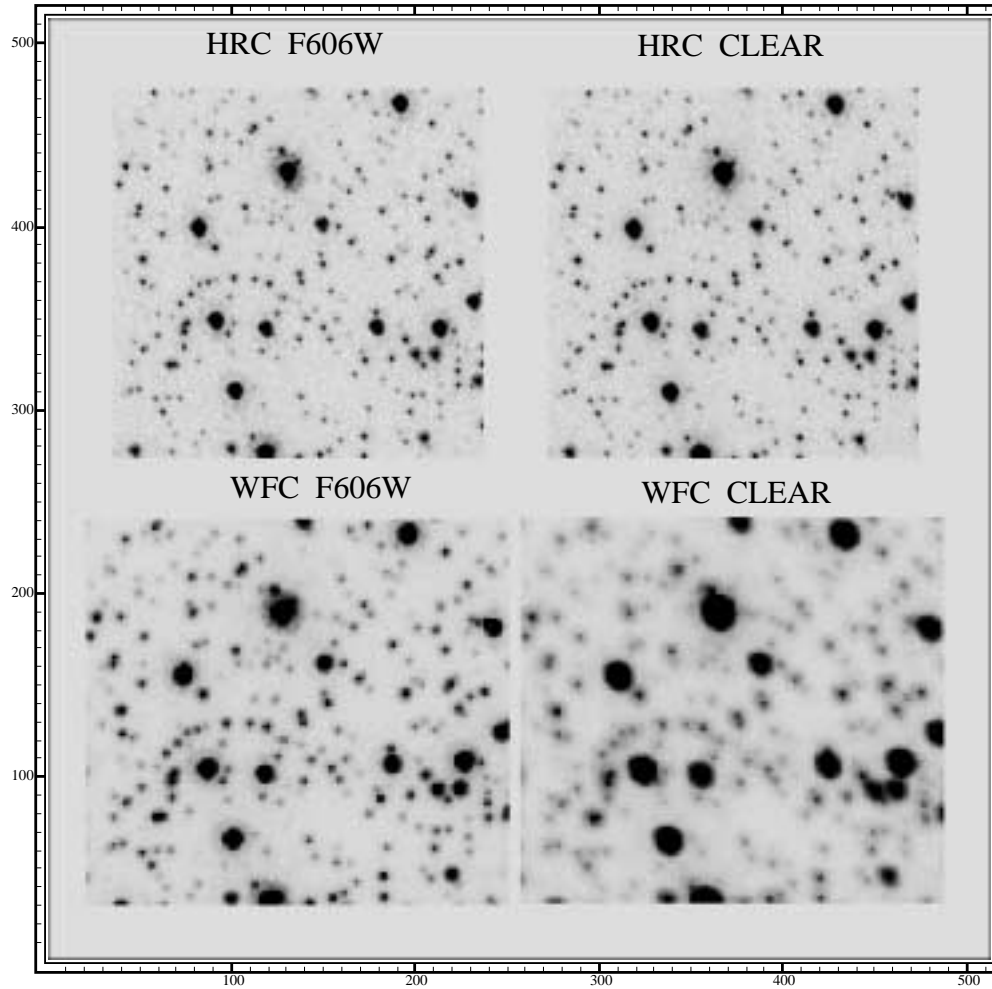


Table 3. F606W and CLEAR PSF Comparison.

| Camera | Filter | FWHM | EE peak pixel |
|--------|--------|------|---------------|
| HRC | F606W | 1.94 | 0.148 |
| HRC | CLEAR | 2.15 | 0.125 |
| WFC | F606W | 1.44 | 0.263 |
| WFC | CLEAR | 2.16 | 0.096 |

For the HRC, use of the CLEAR filter results in only mild-quantitative degradation of the PSF. The significantly larger throughput of the CLEAR coupled with only slightly broadened PSFs could be useful for some science programs (e.g. proper motions of very faint objects where color determination is not a simultaneous goal).

By contrast, the WFC point spread function shows a qualitative degradation with the area enclosed within FWHM doubling and central intensity dropping a factor of three with use of CLEAR.

Data quality and charge traps.

Analysis of the shutter stability test data involved examination of apparent count rates for a large number of stars. Usually these showed flat count rates at the varying exposure times as expected. One star on the HRC, however, showed successively lower count rates at shallower exposures. Inspection of the data showed that the star fell on a charge trap as shown in Table 4 which repeats the same row and column data values at 0.2, 1.0 and 5.0 second exposures. At 5.0s the trap is filled before reaching the star, at 1.0s rows 564-566 at column 200 are lost and at 0.2s rows 564-569 are lost. There is nothing unusual about this behavior, traps are expected and this is the signature expected. In this case, however, the data quality file does not flag these pixels as associated with a trap.

A followup using two internal flats, one at high signal level and the second at low exposure should be analyzed for efficacy in detecting traps. The rate at which traps come and go should be assessed and proper internal calibrations added as needed to keep the data quality files current.

Table 4. Star on HRC near Charge Trap.

| | 0.2 seconds | | | 1.0seconds | | | 5.0seconds | | |
|-----|-------------|-------|-------|------------|-------|-------|------------|-------|-------|
| | 199 | 200 | 201 | 199 | 200 | 201 | 199 | 200 | 201 |
| 574 | 125.6 | 179.5 | 122.3 | 572.1 | 655.8 | 545.6 | 3219. | 3829. | 2966. |
| 573 | 145.1 | 226.2 | 158.8 | 654.2 | 867.6 | 837.7 | 4031. | 4844. | 4550. |
| 572 | 756.1 | 474.3 | 193.8 | 2953. | 1998. | 1004. | 1.9E4 | 1.1E4 | 5087. |
| 571 | 2500. | 1199. | 283.6 | 1.1E4 | 6261. | 1476. | 6.4E4 | 3.3E4 | 6648. |
| 570 | 3070. | 954.7 | 329.5 | 1.6E4 | 9165. | 1862. | 7.8E4 | 4.5E4 | 8451. |
| 569 | 1367. | -0.8 | 173.4 | 1713. | 1361. | 731.3 | 3.5E4 | 2.3E4 | 5571. |
| 568 | 331.5 | 0.17 | 116. | 1713. | 1361. | 731.3 | 7447. | 6382. | 3679. |
| 567 | 171. | 8.009 | 152.9 | 855. | 628.2 | 749.4 | 3540. | 3982. | 3455. |
| 566 | 132.3 | 11.54 | 106.5 | 701.6 | 14.38 | 556.5 | 2638. | 2734. | 2410. |
| 565 | 55.3 | -0.15 | 66.79 | 365.1 | 2.678 | 323.4 | 1346. | 1467. | 1278. |
| 564 | 37.72 | -0.16 | 6.338 | 144.8 | 0.41 | 145.5 | 620. | 710.7 | 624.3 |

Summary.

Timing accuracy, stability, A versus B shutter control dependence and field dependent timing (shading) have been assessed for the HRC and WFC at short exposure times. Adopting as a general guide that default assumptions regarding exposure timing not compromise photometry at the 1.0% level, very few updates are necessary.

Even at the shortest exposures, shutter shading measures did not exceed ~0.5% center-to-edge for either camera. This supports a previous decision to not actively invoke a shading correction in CALACS.

No systematic biases between timing under A and B shutter control reach 0.5% for any average over multiple pairs at any exposure time. This supports not actively utilizing a record of which shutter was used.

Stability of shutter timing is a bit more problematic. For the HRC stability appears excellent, measured as *rms* across several exposures, errors remain well under 0.5%. Only at 0.1s do the HRC exposures exhibit peak-to-peak fluctuations up to ~1.0% (and part of this may be measurement error). At exposure times of 1.0s peak-to-peak fluctuations on the HRC are at only the 0.1% level. The WFC shutter timing stability is not as good, but was also more difficult to quantify given a higher level of systematic errors. Again measured as an *rms* across several exposures errors are well under 0.5%. However, out of 7 pairs of back-to-back 1.0s exposures, two pairs have individual components differing by > 1.3%. (Curiously, a review of CEI specs showed limits on shading, but not a direct spec for accuracy and repeatability.) Where such differences exist on WFC it is always the case that shutter timing when under A control is shorter than the following B exposure. At 0.5s on WFC (where shutter operation is one continuous rotation) the greatest discrepancy A to B remains <0.3%. These results suggest that if generally short WFC exposures are required (where short is taken to be ≤ 2 s), then 0.5s exposures seem stable and likely to support 1% accuracy, but exposures over the range 0.7 to < 2.0s may experience timing fluctuations that could compromise such accuracy. This conclusion regarding WFC exposures is not regarded as robust, but is offered as that most consistent with a simple, and cautious interpretation of the test data.

Adopting a threshold of 0.5% in absolute timing, only 4 exposure times over HRC and WFC need revision. The 0.1s HRC exposure is actually larger than this by 4.1%, a determination secure at $> 10 \sigma$. WFC exposures at 0.5s, 0.7s and 0.8s differ in reality by +1.6%, -1.0% and -0.6% respectively with significance levels in the 5 to 2σ range. For these 4 exposures revised times for CALACS use are recommended in order to support accurate photometry.

Acknowledgements

Jennifer Mack is thanked for helping solve the initial data quality issues associated with out of date flat fields for the CLEAR filters, for quickly updating these flat fields, and for help with relearning use of FRAMEMAKER.

References

Martel, A.R. , Hartig, G., and Sirianni, M. 2001, WFC and HRC Shutter Shading and Accuracy (Feb 2001), http://acs.pha.jhu.edu/instrument/calibration/results/by_item/shutter/shading_accuracy_feb2001/.