FLAT FIELD DETERMINATIONS USING AN ISOLATED POINT SOURCE

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ABSTRACT
The traditional method of measuring ACS flat fields (FF) involves a complicated analysis of multiple observations of a region of the 47 Tuc globular cluster at overlapping field positions. The analysis of the dithered 47 Tuc images suffers from source crowding and possible systematics related to the CTE correction and the high density of sources. New programs 13167 and 13602 avoid these problems by observing a single bright star at several locations around the field of view (FOV) in F435W and F814W. A discrepancy of ~3% with a 10σ level of significance exists between the two FF measurement techniques and is currently unexplained.

1. Introduction

Flat fields (FF) have a low frequency, slowly varying structure (L-flat) and a high frequency, pixel-to-pixel (P-flat) structure (Bohlin et al. 2001). The most straightforward way to measure the relative L-flat response within the ACS FOV is to place an isolated bright star at various sub-array positions in the field and compare the photometry at the different locations. Of course, this method of determining the response could require more orbits than are expended on the usual L-flat method that utilizes the myriad of stars in 47 Tuc, when observed with a few different POSTARGs and roll angles (Mack et al. 2002, hereafter Mack; van der Marel 2003). As a first check on the 47 Tuc results, two standard stars, GD153 (DA1) and KF06T2 (K1.5III), were observed at 13 locations in 2013 with the WFC through F435W and F814W for a total of 52 observations in program 13167. The 13
different sub-array locations require one orbit; and the full pilot program used a total of 4 external orbits, while the required bias frames utilize internal orbits. Somewhat confusing results and wide spacing of the 13 points led to the allocation of a follow up program 13602 with four orbits expended on just F435W, which showed the most deviation from the present L-flat. The 13602 observations doubled the density of sample points to 26 in F435W for each of GD153 and KF06T2. Each observation has a CR-split of two; and exposure times were 6s for GD153 and 56s for KF06T2.

In 13602, five middle positions are repeated to verify the photometry from the 2300 pixel long sub-arrays in 13167; four of the corner positions are redone to verify overall repeatability; and 17 new locations increase the fidelity of any required FF corrections.

2. Data Reduction

In order to update the bright star CTE correction of Bohlin & Anderson (2011), Jay Anderson provided CTE corrected images for 16 sub-array observations located at the bottom of chip 1 or the top of chip 2. The photometry is extracted for the standard one arcsec radius (20 pixels) per the procedure of Bohlin (2012). After CTE correction with the updated formula, the ratios from 13167 of this actual photometry, C, to the synthetic stellar photometry, P, are displayed for F814W in Figure 1, along with the corresponding results at the standard WFC1-1K reference point from Bohlin (2012, 2015). The two synthetic P values are computed from the position independent throughput and the spectral energy distributions (SEDs) gd153_stisnic_006.fits and kf06t2_stisnic_003.fits from CALSPEC1. Figure 2 is the corresponding average results for F435W from 13167 and 13602. The CTE correction is minimal for these heavily exposed images, ranging from 0.999 at the edges near the readout amp to 0.992--0.994 for the data that are ~1800px from the readout amp.

Following the CTE correction, the pairs of adjacent points across the butt between CCD 1 and CCD 2 show excellent continuity, which provides confidence in the results. The maximum discontinuity in the 13167 data across the butt is 0.004 among seven of the eights pairs of star and filter with ~500 pixel separations; the eighth difference is 0.008. Similarly for 13602, three pairs show a maximum

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1 http://www.stsci.edu/hst/observatory/crds/calspec.html
discontinuity of 0.005, while the fourth difference is 0.012. The $1\sigma$ rms scatter among the 12 discontinuities is 0.004, so that 0.003 is an estimate for the $1\sigma$

**Fig. 1** – *Open circles* and associated ratios C/P for 1 arcsec F814W photometry at 13 locations on the 4096x4096 pixel WFC detector (*open circles*) from proposal 13167 along with the WFC1-1K standard reference point (*filled circle*). The red numbers are for KF06T2, while blue is for GD153. The black numbers to the left of the C/P values are the differences between the C/P values for KF06T2-GD153. CCD1 is the top half of the square, while CCD2 lies below.
Fig. 2 – As in Figure 1 for the less uniform F435W filter. Values at the 26 open circles locations are averages over programs 13167 and 13602. The filled circle is the average at the WFC1-K reference point for the annual photometric monitoring since SM4 in 2009 and is offset from the corresponding open circle by (-50,-50) in the 4096x4096 field of view.
uncertainty in any single value of C/P. The 1σ uncertainty from photon statistics that approach a million detected electrons is ~0.001.

The differences, KF06T2-GD153, in C/P for F435W range from -0.022 to +0.031 for 13167 and from -0.012 to +0.032 for 13602, which suggests that the transmission of F435W depends on the stellar type. The corresponding results for the 14 color measures of F814W range only from -0.016 to -0.004 with a mean of -0.009. Thus, if the throughput of the bandpass function for the F814W filter were adjusted to decrease the synthetic photometry P for the blue star (GD153) relative to the red star (KF06T2), then C/P for KF06T2 and GD153 could be consistent to 0.7% for red and blue stars. A bulk shift of the whole F814W transmission function by only -27 Å would fix the -0.009, i.e. 0.9%, mean discrepancy between the synthetic STIS photometry and ACS for red and blue stars (Bohlin 2015). A shift of the long wavelength edge of F814W of ~5 times the bulk shift is required to accomplish the same red-blue star correction and seems unreasonably large.

However for the GD153 and KF06T2 F814W data, the middle set of 5 average F814W C/P values near column 2100 are significantly lower than the 4 average values on the left side, which agree with the 4 right edge values. In particular, the 4 corner averages are consistent at 1.011 +/- 0.002, which makes the center value of 0.980 +/- 0.003 low by 3.1%. Thus, the sub-array data suggests that the current FF is systematically high in the center and does not meet our 1% precision goal. Either the F814W FF does not meet specifications or the 2300 pixel long sub-arrays that are used in 13167 for the middle positions are systematically anomalous.

In the central part of the WFC, the necessity of including a long region in X to capture overscan region is investigated to see if the central FOV observations can utilize small, square sub-arrays that match those used in the corners of the CCD chips. Starting with the raw images, the overscan region is deleted and not used; and then the bias and dark are subtracted. The image is multiplied by the gain and the stripe removal proceeds. The stripe image is formed from a simple median of each row, which is optimal for these sparse field data. The subtraction of such a stripe image compensates for skipping the normal overscan subtraction step. The de-striped image is divided by the flat field; and the pairs of cr-split=2 images are processed by the IDL cosmic ray rejection routine acs_cr.pro, which has parameters mult=0.3, nsi=[6.5,5.5,4.5], and dilation=2.1. The latter two parameters match the ACS pipeline. Finally, the pixel-area-map correction is applied and the photometry
is extracted with *apphot.pro* with the standard background region and a 1 arcsec radius aperture; then the photometry is corrected for CTE losses.

The photometry for 13167, as derived according to the above recipe from the *_raw* images without overscan, differs from the pipeline *_crj* results by $\leq 0.0005$ in any of the 52 measured C/P values. Consequently, 13602 uses 400x400 pixel sub-arrays without overscan at all 26 field positions for both the bias and stellar observations. Unfortunately, the pipeline cannot process bias observations with no overscan, so super-bias reference files for 13602 are defined by the median of the 21 repeated bias frames at each pixel; and the data processing in IDL begins with the *_raw* files and produces photometry, as detailed above. The data for one position are also processed with IRAF using the CR-reject algorithm to make the super-bias file, and the pipeline CALACS to produce a de-striped *_crj* file. The photometry from the IDL and CALACS processed files agree to 0.01%.

Five middle positions in 13167 for F435W are repeated in 13602 for both stars. The average difference and $1\sigma$ rms of the 10 pairs of matching 13167-13602 middle photometry points near column 2100 are +0.002 and 0.003. Including eight more pairs from the four matching CCD corner positions, the average difference and $1\sigma$ rms of the 18 pairs of matching 13167-13602 photometry are +0.003 and 0.004. Thus, the earlier estimate of 0.003 from continuity across the butt of the two chips is a good estimate of the uncertainty in any individual photometry measure.

### 3. The Flat Field Inconsistencies

The above suggestion that the sub-array FF measures vary significantly from the center to the corners motivates Figure 3, which illustrates the systematic variation of the GD153 and KF06T2 photometry as a function of distance from the center for both F435W (blue) and F814W (red). The radial distance in pixels is relative to the (2048,2048) center pixel in the 4096x4096 pixel FOV. The C/P values are squares for GD153 and circles for KF06T2; and separate least-square linear fits appear for the 26 points from proposal 13167 for F814W and the 78 points from both 13167 and 13602 for F435W. Four more (*large*) points from the average response since SM4 at the WFC1-1K reference point are also included in the fits. The general trend for both filters over the center to corner distance of 2534 pixels is 3-4% with a 7-8$\sigma$ level of significance. The corner pixels are ~256 pixels from the edges of the FOV.
Fig. 3 – C/P vs. distance from the center of the 4096x4096 WFC detector for the sub-arrays from programs 13167 and 13602. The F435W values are blue and the F814W are red. Symbols are the GD153 (squares) and KF06T2 (circles) values. The four large, double symbols are 512 pixels from the top and from right edge at the WFC1-1K sub-array reference point, where the absolute flux calibration is anchored. Both filters show a radial dependence of over 3% with a 7-8σ significance.

The red squares (GD153) are offset from the corresponding red circles (KF06T2) because of the need for a bandpass correction, as discussed above. Similarly for F435W, the blue circles tend to lie above the blue squares; but the amount of offset is not as consistent as for F814W. Thus, the FF for F435W seems to differ by more than 1% for stars of different color temperature (see Bohlin 2015).
3.1 Could Errors in the CTE Correction be a Problem?

Any error in the CTE correction would be a maximum near \(y=2048\) in the 4096x4096 FOV, i.e. the farthest rows from the readout amplifiers, and a minimum near the top and bottom of the WFC FOV, while any CTE error should be independent of the X-pixel location. Figure 4 shows \(C/P\) vs. X-location at \(\sim256\) pixels from top or bottom (dashes) and at \(\sim256\) pixels from the central butt of the two CCD chips (solid). The data points represent the average over both stars and both proposals but are shown separately for F435W (blue) and F814W (red). All deviations from unity are indicative of errors in the current FFs or in the sub-array data from proposals 13167 and 13602 (modulo small vertical shifts for any update to the absolute flux calibration that would be the same for all the red or all the blue points). Figure 1 shows that the center point for F814W is missing for the Y-location \(\sim256\) pixels above the central butt. Thus, there are seven traces in Figure 4: three for F814W (red) and four for F435W (blue). The points connected by dashed lines for the top and bottom regions always lie above the central measures (solid lines) for both filters, as would be expected for a CTE correction error. However, the amount of this error in the CTE correction would be \(\sim3\) times the \(\sim0.7\%\) correction in Y that has already been made. Furthermore, the central point is always lower than the left and right points by 1-3\% for all seven traces. Thus, there is a systematic error that is a function of the X-pixel location, which CANNOT be caused by the traditional Y-dependent CTE correction. The central F814W point near \(x=2100\) lies \(\sim3\%\) below the corner points, which is a \(10\sigma\) effect and must have a physical explanation.
Fig. 4 – C/P vs. X-pixel location on the 4096x4096 pixel WFC detector for sub-arrays from programs 13167 and 13602. The F435W values are blue and the F814W are red. Dashed lines connect points near the top and bottom of the WFC FOV, while solid lines connect locations in Y near the central butt of the two CCD chips. C/P values are averages over both stars.
3.2 Could the Flat Field have Changed?

3.2.1 Pipeline Flat Fields

The flat field used to reduce all the 13167 and 13602 F435W data is qb12257gj_pfl.fits with a USEAFTER of July 04 2006, while the corresponding flat for F814W is qb12257pj_pfl.fits. Only two sets of WFC FFs are used for ACS data processing, the original FFs for the CCD set point of -77 C and the new FFs for the -81 C operating temperature, which was established on 2006 July 4. The differences in the two sets are minor; for example for F435W, the original flat n6u1258nj_pfl.fits differs from qb12257gj_pfl.fits by less than 1% anywhere in the FOV. Thus, the deviations from unity in Figures 3-4 cannot be attributed to the change of the FF reference file on 2006 July 4.

3.2.2 Actual Changes in the FFs

Could there be actual changes in the FFs that are not tracked by the reference file FFs? This possibility is investigated by analyzing the monitoring observations of the internal tungsten FFs, which have been routinely obtained since 2002 for F435W, F625W, and F814W. For example, Figure 5 shows the changes in the internal FF data in 100x100 pixel boxes at the four corners of the WFC centered 256 pixels in X and Y from the ABCD readout amplifiers (black) and near the center of the detector at the four points 1792 pixels in X and Y from the readout amps. Before the switch to the -81 C CCD set point on 2006 July 4 (Gilliland et al. 2006), the signal shows a monotonic decline; and after SM4 in 2009 the signal is constant at all eight locations in the flat field corrected *_flt.fits files. Any differential change among the eight positions is less than 0.2%, which cannot account for the ~3% discrepancies shown in Figures 3-4. To check for changes at all locations, not just the eight points in Figure 5, the last internal flats in 2015 are divided by the first observations in 2002 for all three monitored filters. There is less than +/- 0.4% change in the L-flats over the 13 year ACS lifetime, as illustrated for F435W in Figure 6.

Thus, the L-flats have not changed significantly and do not need to be updated with a recent USEAFTER date. The original L-flats derived in 2002 and slightly modified by Gilliland et al. (2006) remain the same, so that the only question is whether those
Fig. 5 – Change in the WFC F435W internal FF monitor data at 8 positions. Each point is the average signal in a 100x100 pixel box centered at the coordinates indicated on the plot in the 4096x4096 pixel field of view. The slope of the least squares linear fit to the data before 2006.5 is also written for each of the 8 positions, where the black data are near the 4 corners of the field and the 4 red sets are near the field center. Each of the 8 loci are normalized to unity at the value of their linear fit at 2002.16 and offset by 0.04 (dashed lines), so that unity for the lowest curve falls at 0.72. All 8 points show nearly the same change.
Fig. 6 – Change from 2002 to 2015 in the WFC F435W internal FF monitor data over the full FOV.
original L-flats are wrong or the sub-array checks are wrong. Any change that is the same over the entire FOV is accounted by the absolute flux calibration.

3.3 Comparison with the Pipeline FFs made from 47 Tuc Observations

The current pipeline flats are based on five pixel radius photometry for the 47 Tuc data from program 9018 with 9 dither points of 22 arcsec steps in X and Y (Mack). Three relatively bright stars that lie near the upper right corner of the WFC in one extreme dither of 44,44 arcsec and that are also near the center for the other extreme dither of -44,-44 arcsec are chosen for the L-flat check. (The brightest stars are saturated and unrecoverable, because gain=1 was used.) Photometry for each star should be the same, regardless of position on the WFC detector, if the current FFs are correct. Figure 7 presents the results for the 9 dithers for each of the three stars for a total of 27 points for each of F435W (blue) and F814W (red). Points are normalized to the average photometry for each star and then renormalized to the value of the linear fits at the WFC center distance of zero. In Figures 3-4, the corner points are offset from the WFC center by 2534 pixels, where the delta in the FF response is 3-4%. However, Figure 7 shows only a 0.5% slope over the same distance and is consistent with a perfect response of unity everywhere within 1σ. Similar results are found for the photometry with a 20 pixel (1 arcsec) radius and for the CTE corrected files *crc.fits and *flc.fits, as expected, because there are little CTE losses for these early observations. Thus, the FFs derived by Mack in 2002 have no error in the analysis technique that is larger than 0.5% with a 1σ uncertainty of 0.5%, so that the 3-4% difference in Figure 3 over the same 2534 pixel center-to-corner distance from the sub-array data is a 6-8σ discrepancy for F435W and F814W.
Fig. 7 – Check of the 47 Tuc data used by Mack to derive the WFC L-flat. Three stars represented by different symbols sample the FOV at nine dither points. The 5-pixel radius photometry from the *crj.fits files is the same data used by Mack to derive the L-flat. Each star is normalized to the average of its 9 measures; and for a perfect FF and no noise, every point should lie at unity. The slopes of the least square linear fits for F435W (blue) and F814W (red) differ from unity by only a 1σ of 0.5% over the range of Figures 3-4, where the sub-array data show a center-to-corner gradient of more than 3%.

4. Conclusion

The new sub-array mapping observations of GD153 and KF06T2 suggest that the central region of the detector produces photometry that is ~3% low compared to the four corners for F435W and F814W. Excluding analysis errors, explanations include the possibility that sub-array sensitivities depend on location or that there is some CTE transfer losses in the serial X direction, in addition to the well characterized losses in Y during the parallel transfers from row-to-row. The symmetry of the
discrepancy in Figures 3-4 could be explained by an unlikely under-correction for CTE losses in Y combined with an even more unlikely CTE loss during the serial transfers of charge in the X direction.

One final possible solution to the quandary is that sub-array and full readout of both chips using the standard 4 amp configuration do not record the same signal for sub-arrays near the center of the WFC FOV. At the WFC1-1K reference point, full frame signal does agree with the sub-array results to 0.2% for two full frame observations of P330E and KF06T2 in F850LP from program 11889; but sub-array vs. full-frame has never been checked near the center of the WFC field. An orbit in Cycle 23 will be devoted to cross-calibrating full frame and sub-arrays near the center of the WFC FOV.

REFERENCES


