

ACS Flat Fields and Low-order “L-flat” Corrections from Observations of 47 Tucanae

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Abstract. The uniformity of the WFC and HRC detector response has been assessed using multiple dithered pointings of 47 Tucanae. By placing the same stars over different portions of the detector and measuring relative changes in brightness, low frequency spatial variations in the response of each detector have been measured. The original WFC and HRC laboratory flat fields produce photometric errors of 6 to 18 percent from corner-to-corner. The required low-order correction (L-flat) has been applied to the lab flats, and new flat fields have been delivered for use in the calibration pipeline. Initial results indicate that the photometric response for a given star is now the same to $\sim 1\%$ for any position in the field of view. A comparison of the improved flat fields with high signal observations of the bright earth at 3300 \AA and with preliminary skyflats at 7700 \AA also shows agreement to within $\sim 1\%$.

1. Introduction

In 2001, flat field images for the ACS detectors were produced on the ground using the RAS/HOMS (Refractive Aberrated Simulator/Hubble Opto-Mechanical Simulator) with a continuum light source. These flats include both low frequency (L-flat) and high frequency pixel-to-pixel (P-flat) structure. The RAS/HOMS provides an external, OTA-like illumination above its refractive cutoff wavelength of $\sim 3500 \text{ \AA}$. Because the RAS/HOMS optics are opaque below 3500 \AA on-orbit observations of the bright earth are used to create the UV flats for the HRC. The intrinsic pixel-to-pixel rms of the detector is $\sim 0.5\%$. Thus, to avoid any significant loss of signal-to-noise when applying the flat fields to the science data, the Poisson counting statistics of the external flats are $\sim 0.3\%$, i.e., at least 100,000 electrons/pixel. For a detailed discussion of creating the ground flat reference files, see Bohlin et al. 2001.

To assess the accuracy of the ground flats, multiple dithered pointings of the globular cluster 47 Tucanae were made. By placing the same star over different portions of the detector and measuring its relative changes in brightness, errors in the laboratory flats have been discovered. This paper is devoted to a discussion of the L-flat corrections derived for the WFC and HRC detectors. For more a more detailed description of the L-flat program for the WFC, see Mack et al. 2002.

Sky flats may eventually replace the corrected ground flats and will be built up from numerous GO images of sparse fields. To achieve the required 100,000 electrons/pixel at F606W, for example, ~ 3 weeks of constant observing would be required. Preliminary low-signal sky flats for F775W are compared below with the derived stellar L-flat.

Internal lamp flats are also part of the ACS flat fielding program but are relevant for monitoring purposes only, since these flats have a different illumination than the external flats. Specifically, the internal lamps blur the shadows of the dust motes and cannot properly correct for new motes or for existing motes which may have shifted.

2. Observations

For the WFC and HRC detectors, the accuracy of the ground flats is assessed using observations of the globular cluster 47 Tucanae (NGC 104). The WFC observations are offset 6 arcmin from the cluster center to minimize the effects of crowding which can complicate the sky subtraction when performing aperture photometry. The L-flat observing program is summarized in Table 1 which includes the target RA and Dec, the dither step size, and the filters used for imaging. Each WFC image contains ~ 6000 stars of sufficient signal-to-noise at each of the 9 dither positions, while each HRC image contains ~ 3000 stars.

Table 1. L-Flat Observations of 47 Tucanae

Detector	Program	Dither Step	RA	Dec	SDSS Filters	BVI Filters
WFC	9018	22" (11% FOV)	00:22:37.20	-72:04:14.0	F775W	F435W
					F850LP	F555W
						F606W
						F814W
HRC	9019	6" (23% FOV)	00:24:06.52	-72:05:00.6	F475W	F435W
					F625W	F555W
					F775W	F606W
					F850LP	F814W

For each detector/filter combination, the dither pattern consists of 9 pointings along a diagonal cross, where the step size in X and Y is 22" for the WFC and 6" for the HRC. Since the field size is $\sim 200''$ for WFC and $\sim 25''$ for the HRC, each step is a large fraction of the detector field of view, as indicated in Table 1.

The 9-point dither pattern is illustrated in Figure 1 for each detector, where the size of each dither in pixels is shown with respect to the size of the WFC and HRC detectors. The central dither position for each detector is shown in bold. Stars which were observed in at least three images are overplotted on the diagram.

3. Matrix Solution

A matrix-solution program was developed by R. van der Marel for deriving the low-frequency flat field corrections from the dithered, stellar point-source photometry. Separate solutions for each of the filters listed in Table 1 were derived using this algorithm. The details of this code are described in a separate *HST Instrument Science Report*, currently in progress.

To summarize, the observed magnitude of a star at a given dither position is assumed to be the sum of the true magnitude of the star plus a correction term that depends on the position on the detector. The correction term represents the L-flat. The L-flat, when given in magnitudes, can be expressed as the product of fourth-order polynomials in the detector

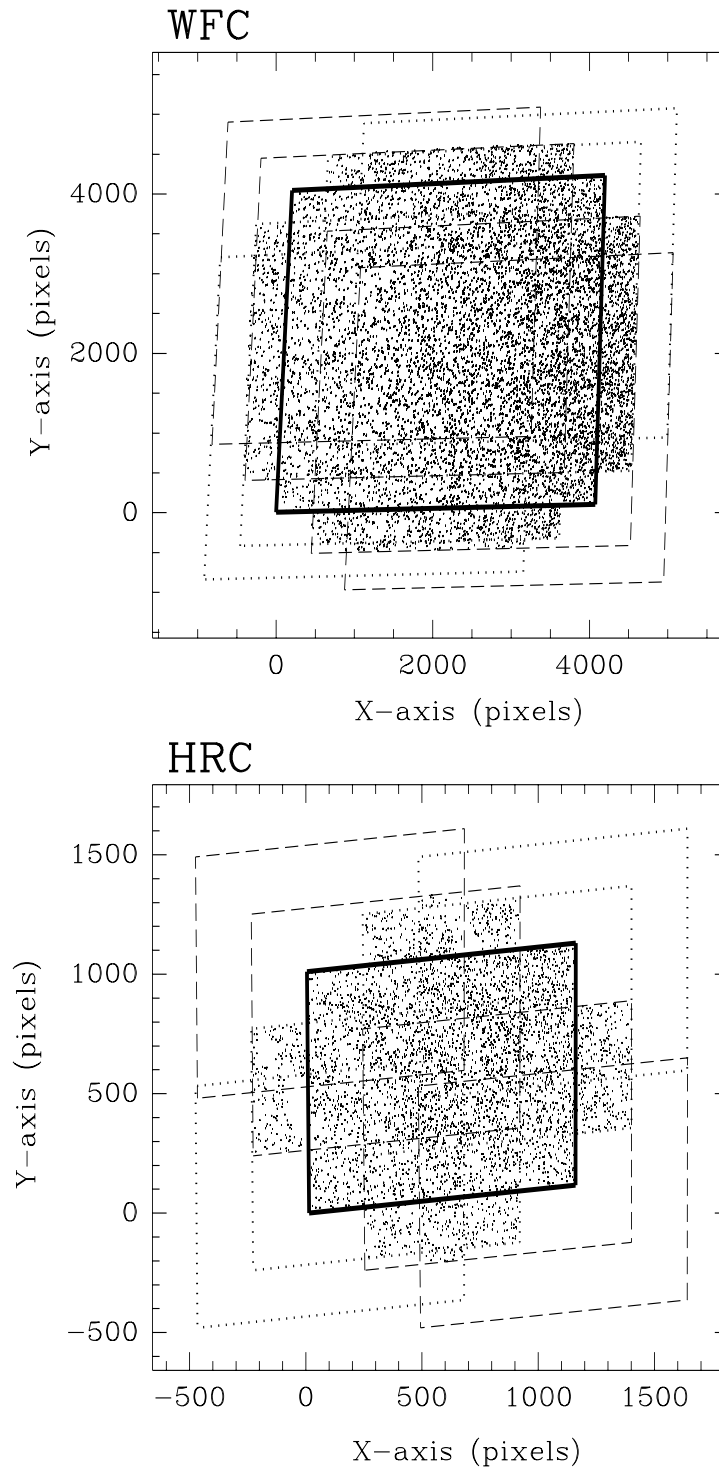


Figure 1. Nine-point dither pattern, in geometrically-corrected pixel coordinates, for the WFC and HRC L-flat observations. The central dither for each detector is shown in bold. Each WFC step (dotted and dashed lines) is ~ 440 pixels (11% FOV) in x and in y . Each HRC dither is ~ 240 pixels (23% FOV). Stars which were observed at least three times are plotted.

x and y coordinates. When a set of multiple dithered observations is available for a given star field, the determination of both the L-flat and the true instrumental magnitude of each star can be written as an overdetermined matrix equation. This equation has a unique minimum χ^2 -solution that can be efficiently obtained through singular-value-decomposition techniques.

The matrix solution requires as input the magnitude of each star and its uncertainty. The appropriate photometric aperture is chosen which includes $\sim 80\%$ of the encircled energy. This radius corresponds to 5 pix for the WFC and 7 pix for the HRC. Uncertainties from the sky background and from neighboring stars increase at larger radii. Sigma clipping is employed to reject stars having large photometric residuals with respect to the variation in the L-flat. These rejected outliers are mostly due to cosmic rays, image saturation, or stars falling at the edge of the detector.

In Figure 2, the L-flat solutions derived for F555W are shown for the WFC and HRC. The residual of the stellar magnitude with respect to the predicted magnitude is displayed, where stars in the upper left of the WFC (HRC) are too faint (bright) after pipeline calibration with the original ground flats, and stars in the lower right are too bright (faint). There is a continuous gradient in the L-flat along the diagonal of the detector, which corresponds to the axis of the maximum geometric distortion. This gradient is of order 10% from corner to corner and varies with wavelength (see Table 2.) The diagonal in the opposite direction shows no systematic gradient, and stars falling along this diagonal require no correction. Because the detectors are rotated approximately 180 degrees with respect to one another on the sky, the direction of the L-flat gradient for the WFC and HRC detectors is reversed.

Assuming a simple linear dependence on wavelength, the L-flat correction for the remaining wide, medium, and narrow-band WFC filters is derived. The pivot wavelength of each filter is used for the interpolation, where the resulting L-flat correction is equal to the weighted average of the L-flat correction for the two filters nearest in wavelength.

A comparison of ACS F550M with WFPC2 F547M photometry indicates that the ‘‘interpolated’’ L-flat has errors that are no larger than $\sim 2\text{--}3\%$. Other flats which were derived via interpolation are the HRC and WFC narrow-band filters: F502N, F550M, F658N, F660N, F892N and the WFC broad-band filters: F475W, F625W. Further study is required to achieve uncertainties of 1% for these flats.

Table 2. Required Corrections to the Ground Flats, Expressed As a Percent Gradient from the Upper-left to the Lower-right Corner

Filter	WFC	HRC
F435W	16%	7%
F475W	–	7%
F555W	10%	6%
F606W	14%	7%
F625W	–	7%
F775W	13%	8%
F814W	15%	9%
F850LP	18%	12%

4. Comparison with In-Flight Sky Flats

To verify the L-flats derived from point source photometry, sky flats were created by J. Blakeslee using WFC exposures of the Hubble Deep Field- North which contains a large

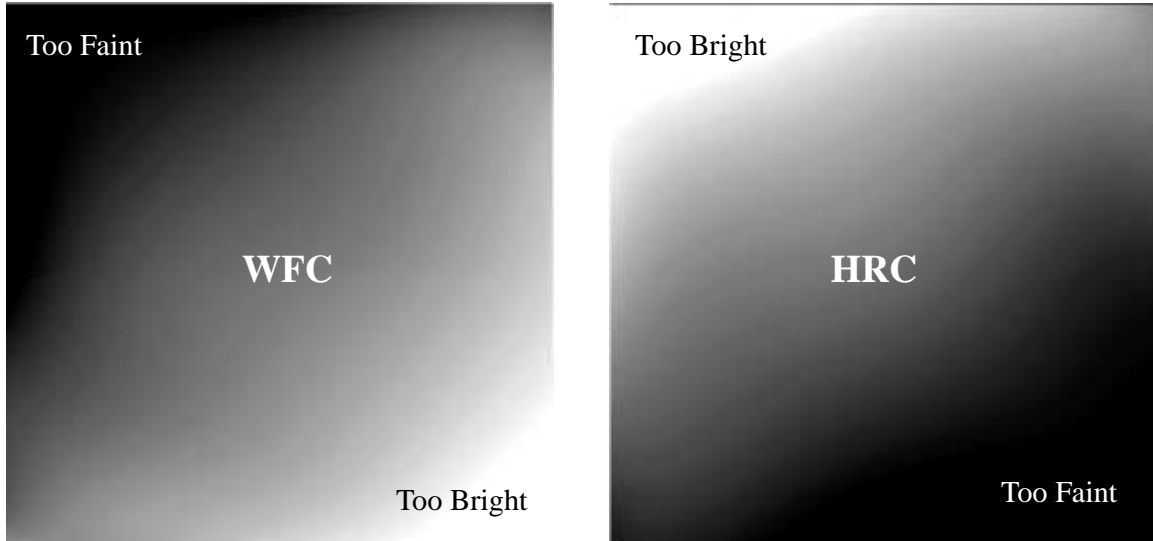


Figure 2. Low-order flats derived for F555W from the matrix-solution code. The WFC (HRC) variation from corner-to-corner is 10% (6%). Black indicates that the ground flats produce photometry which is too faint with respect to the true stellar magnitude; white indicates that photometry is too bright.

amount of “blank” sky. For F775W, the combined exposure is 4500 sec. Because this exposure is not high enough signal-to-noise to reproduce the pixel-to-pixel structure of the detector, SExtractor was used to fit a smooth, low-order bicubic spline to the sky background, after first masking all detected sources. The resulting image was then normalized by its mean countrate to produce the sky flat field. The ratio of the F775W sky flat to the ground flat, corrected using the photometrically derived L-flat, shows residuals of less than 1% which are relatively flat across the detector. Thus, the L-flat derived using point-source photometry is nearly identical to the L-flat derived from an extended source.

For the ultraviolet HRC filters, the pixel-to-pixel flats are derived from observations of the bright earth. To verify the L-flat technique at visible wavelengths, stellar L-flat observations using the F330W filter were obtained. Then, the ground flats are corrected by the derived ultraviolet L-flat and divided by the earth flat to create a residual image. Again, residuals are less than 1% over the detector. The corner-to-corner gradient in the L-flat correction is $\sim 5\%$ for F330W, consistent with the trend in L-flat gradient with wavelength seen in Table 2.

As more precise, high signal-to-noise sky flats are built up over the next year, detailed comparisons with L-flat solutions from the 47 Tuc data will be possible, with the anticipated redelivery of improved flat fields using the sky flats themselves.

5. L-flat Verification Using 47 Tuc Color-Magnitude Diagrams

To verify the photometry derived after the L-flat corrections are applied, features in the color magnitude diagram for 47 Tucanae are examined. More than 3500 stars were matched in the F435W, F555W and F814W filters for the WFC, from one magnitude above the cluster turnoff to four magnitudes down the main sequence. Zero points were added to each band-pass to approximately match the position of the 47 Tuc color-magnitude diagram (CMD) from numerous published sources using standard Johnson-Cousins B , V , and I photometry.

In Figure 3, the V vs. $B - V$ and V vs. $V - I$ color magnitude diagrams are shown. The relevant comparison is not the consistency of the zero points (which are arbitrary for this

test), but rather the consistency of CMD features for stars observed over different portions of the detector. In particular, the L-flat corrections are largest in the upper-left and lower-right corners of the detector, so it is natural to consider whether CMDs for these regions are consistent.

The nearly horizontal CMD region, which is associated with the transition to subgiants, can be used to test for any positional dependence. Twenty stars were selected from each corner of the 47 Tuc image for the region near $V = 17.15$ in the CMD. The difference in V magnitude measured between the upper-left and lower-right corners is zero to within 0.6% for regions which are separated by more than 2000 pixels along the diagonal. A test along the opposite diagonal gives a similarly small change.

The nearly vertical CMD region near $V = 17.7$, which is associated with stars nearing the main sequence turnoff, can be used to check for positional dependencies in B and I relative to V . These tests confirm that the photometry is consistent to within several tenths of a percent over the chip.

Photometry using the new LP-flats for 47 Tuc in the B , V , and I bands yield excellent CMDs. The ACS CMDs are noticeably tighter than CMDs published from much more extensive WFPC2 observations within the same field (Zoccalli et al. 2001). These results confirm that any field dependence in the point source photometry, caused by inaccurate flat fields, geometric distortion effects, and aperture corrections, is now corrected to within 1%.

6. Summary

- Low-frequency flat field corrections have been created for most ACS modes, where the required correction to ground flats is ~ 6 – 18% . The reference files now in the calibration pipeline are accurate to $\sim 1\%$ over the FOV for most modes. These files are revised LP-flats, derived by dividing the original ground P-flats by the derived L-flat corrections.
- For filters which were not directly observed, an interpolated L-flat was derived from the weighted average of the L-flats using the two filters nearest in wavelength. Testing indicates that the interpolated flats are accurate at the 2–3% level. Further study is required to correct these filters to the 1% level.
- L-flat corrections for the SBC are underway. Observations of the UV-bright star cluster NGC 6681 were taken in program 9024 for filters F125LP and F150LP. The corrected SBC reference files should be available in the calibration pipeline in early 2003.
- Determination of the L-flats for other modes, including the ramp filters, the polarizers, the coronagraph, and the dispersers is still required.
- In the ultraviolet, Earth flats will be used to create high signal-to-noise P-flats for the HRC. Earth flats for the bluest HRC and WFC filters will be used to verify the stellar L-flats derived for these filters.
- Sky flats will be built-up over time to compare with the corrected ground flats and may eventually replace them. To achieve the required signal to reproduce the pixel-to-pixel structure of the flats, a total of several weeks of integrated time is required.
- Observers are encouraged to check the ACS web site for the latest flat field reference files available for recalibration.

http://www.stsci.edu/hst/acs/analysis/reference_files/flatimage_list.html

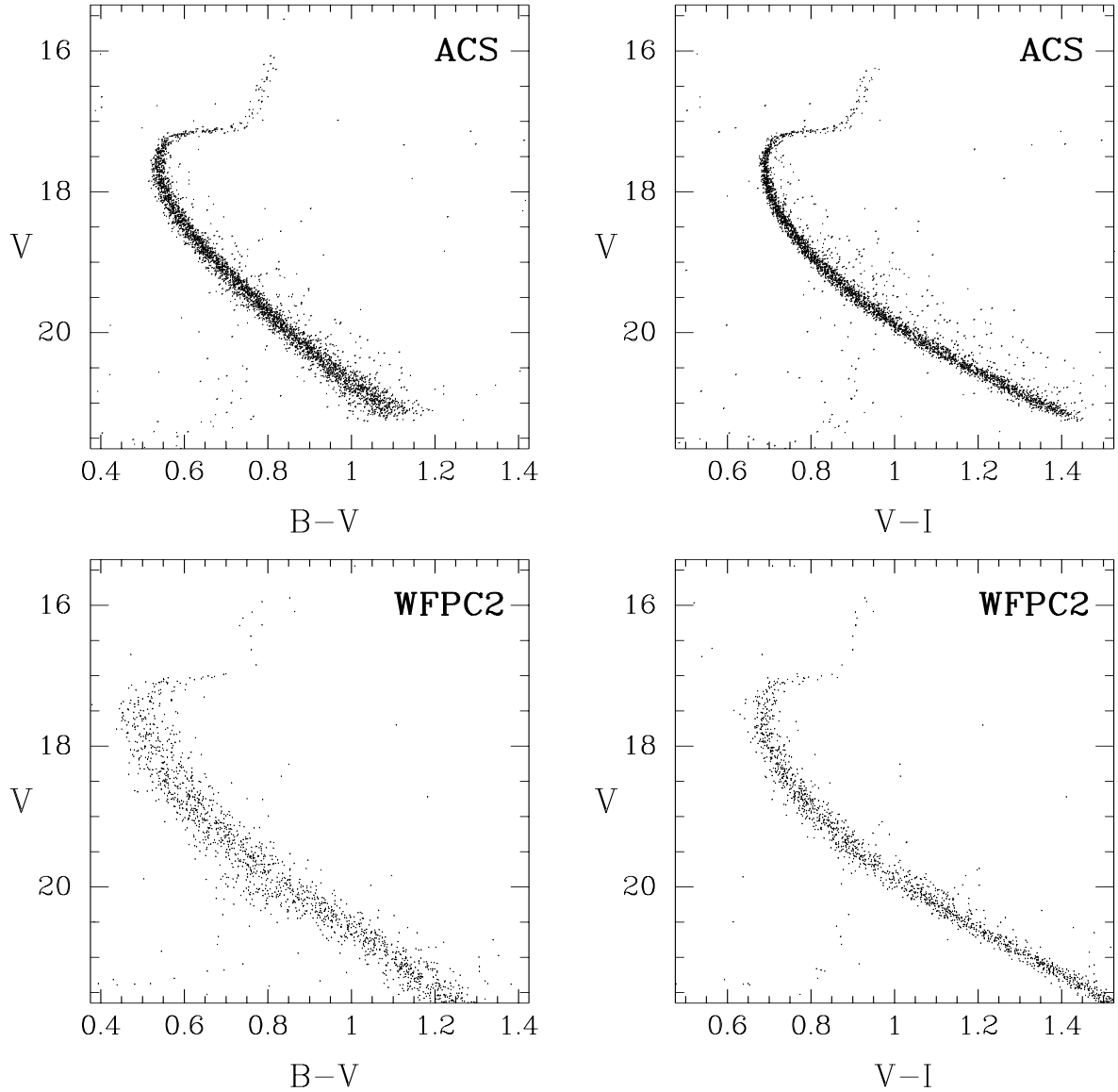


Figure 3. Color magnitude diagrams for WFC observations of 47 Tucanae derived from B , V , and I photometry after applying the L-flat correction. Each WFC exposure is 60 seconds. A precise transformation to the standard B , V , I system has not been attempted, and small color terms may be unaccounted for in the ACS plots. The WFPC2 CMDs are shown for the same field (Zoccali et al. 2001).

Acknowledgments. We would like to thank the ACS Calibration and Photometry Working Group for valuable brainstorming sessions related to this work. We also express thanks to Don Lindler for creating the matched-coordinate lists, Gehrhardt Meuer for useful comments and suggestions, Colin Cox for input on velocity aberration, and Tom Brown for sharing his insights on creating L-flats for STIS.

References

- Bohlin, R. C., Hartig, G., & Martel, A. 2001, *Instrument Science Report ACS 01-11* (Baltimore: STScI)
- Mack, J., Bohlin, R. C., Gilliland, R. L., van der Marel, R., Blakeslee, J. P., & de Marchi, G. 2002, *Instrument Science Report ACS 02-08* (Baltimore: STScI)
- Zoccali, M., Renzini, A., Ortolani, S., Bragaglia, A., Bohlin, R., Carretta, E., Ferraro, F. R., Gilmozzi, R., Holberg, J. B., Marconi, G., Rich, R. M., & Wesemael, F. 2001, *ApJ*, 553, 733