Parallel imaging data from the HST Frontier Fields campaign (Lotz et al. 2017) have been used to compute sky flats for the ACS/WFC detector in order to verify the accuracy of the current set of flat field reference files. By masking sources and then co-adding many deep frames, the F606W and F814W filters have enough combined background signal that errors from Poisson statistics are <1% per pixel. In these two filters, the sky flats show spatial residuals ~1% or less. These residuals are similar in shape to the WFC flat field ‘donut’ pattern, in which the detector quantum efficiency tracks the thickness of the two WFC chips. Observations of blue and red calibration standards measured at various positions on the detector (Bohlin et al. 2017) confirm the fidelity of the F814W flat, with aperture photometry consistent to ~1% across the FOV, regardless of spectral type. At bluer wavelengths, the total sky background is substantially lower, and the F435W sky flat shows a combination of both flat errors and detector artifacts. Aperture photometry of the red standard star shows a maximum deviation of 1.4% across the array in this filter. Larger residuals up to 2.5% are found for the blue standard, suggesting that the spatial sensitivity in F435W depends on spectral type.

I. Introduction

The ACS/WFC flats were derived from ground test data and achieve Poisson errors of ~0.3% per pixel. On-orbit dithered observations of 47 Tucanae revealed photometric deviations across the field of view, requiring low-frequency corrections ~10% to the ground flats. These were implemented in 2002 via an improved set of flat reference files. In 2006, the WFC temperature setpoint was reduced from -77°C to -81°C in order to mitigate the growing population of hot pixels. The new, lower temperature required changes to the flats at the level of ±0.3%. The flat field reference files remain unchanged since 2006, and a comparison of internal tungsten lamp flats from 2006 and 2017 confirm
that the low-frequency spatial structure of the flat is consistent to ~0.2%, after accounting for temporal changes in the brightness of the lamp. A more detailed history of the ACS/WFC flat field reference files is provided in Bohlin et al. (2017), with citations to prior work.

To verify the precision of the current set of reference files, red and blue photometric standards were positioned at various locations across the detector field of view in F435W and F814W (Bohlin & Grogin 2015, Bohlin et al. 2017). Aperture photometry in F814W using a large 1” annulus shows variations ~1% or less regardless of spectral type, confirming the accuracy of the 2006 reference file, even after nine years. Photometric residuals in the F435W filter are consistent to ~1% for the red standard but show deviations ~3% for the blue standard. The authors conclude that the spatial response in this filter is dependent on the source color and provide 2D maps for correcting the flat field based on spectral type.

With the goal of verifying spatial variations derived from aperture photometry, this report describes an independent assessment of the flat field accuracy based on sky flats. Imaging data from the Frontier Fields (FF) program obtained over three years in six separate parallel fields is described in Section 2. The technique used to build the sky flats, including source masking, normalizing by the mean background, and averaging the data from all six fields by filter is highlighted in Section 3. The combined sky flats are described in Section 4 and provide an estimate of the flat field accuracy for sources similar in color to the sky. Due to the lower background at blue wavelengths, the F435W sky flats are dominated by artifacts, and these are discussed in Section 5. A comparison of the sky flat residuals with the repeatability of aperture photometry across the array for two HST photometric standards is provided in Section 6. Finally, the Appendix of this report details a comparison of F435W sky flat computed from a separate study using a larger sample of archival imaging data.

II. Observations

With the ACS/WFC and WFC3/IR detectors observing in parallel, the FF program obtained ~70 orbits of six strongly lensed cluster fields and six adjacent ‘blank’ fields totalling ~840 orbits over a period of three years (Lotz et al. 2017). With a survey of this depth, there is enough signal from the sky background to create flat fields with Poisson errors of ~1% or better in the ACS/WFC detector.

Table 1 summarizes the full set FF parallel observations, including the name of corresponding cluster field, the program ID, and the range of dates during which ACS data were obtained in parallel with WFC3. For each of the six parallel fields, 36 images were obtained in F435W, 20 images in F606W, and 84 images in F814W. For optimal orbit packing, the images in any given filter range in exposure time from 1100-1500 seconds, with a mean and 1-sigma range of 1260±60 sec. Table 2 gives the total number of exposures in all six cluster parallels, the combined exposure time, the cumulative sky background, and the mean countrate measured in each of the three broadband filters.
Table 1. Frontier Fields parallel imaging data (PI=Lotz).

<table>
<thead>
<tr>
<th>Associated Cluster Field</th>
<th>Proposal</th>
<th>Date of Observations</th>
<th>Flashed Darks?</th>
<th>Mean F435W Sky (e/s)</th>
<th>Ecliptic Latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abell 2744</td>
<td>13495</td>
<td>25 Oct 2013 – 28 Nov 2013</td>
<td>No</td>
<td>0.0215</td>
<td>-29.0</td>
</tr>
<tr>
<td>MACSJ0416.1-2403</td>
<td>13496</td>
<td>31 Jul 2014 – 01 Sep 2014</td>
<td>No</td>
<td>0.0181</td>
<td>-44.5</td>
</tr>
<tr>
<td>MACSJ1149.5+2223</td>
<td>13504</td>
<td>20 Nov 2014 – 07 Jan 2015</td>
<td>No</td>
<td>0.0242</td>
<td>+19.3</td>
</tr>
<tr>
<td>MACSJ0717.5+3745</td>
<td>13498</td>
<td>19 Feb 2015 – 24 Mar 2015</td>
<td>Yes</td>
<td>0.0264</td>
<td>+15.4</td>
</tr>
<tr>
<td>Abell S1063</td>
<td>14037</td>
<td>21 Apr 2016 – 30 May 2016</td>
<td>Yes</td>
<td>0.0214</td>
<td>-33.9</td>
</tr>
<tr>
<td>Abell 370</td>
<td>14038</td>
<td>27 Jul 2016 – 11 Sep 2016</td>
<td>Yes</td>
<td>0.0278</td>
<td>-16.4</td>
</tr>
</tbody>
</table>

Table 2. Properties of the sky flats, including the number of ACS orbits (images) per parallel field, the total number of images per filter, the combined exposure time in hours, the cumulative signal in electrons (after dark subtraction), and the estimated Poisson error.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Number of images per parallel field</th>
<th>Total number of images</th>
<th>Total Exposure (hours)</th>
<th>Cumulative Signal (10^3 electrons)</th>
<th>Poisson Error</th>
<th>Mean Sky (e/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F435W</td>
<td>36</td>
<td>216</td>
<td>76.3</td>
<td>6.4</td>
<td>1.3%</td>
<td>0.023</td>
</tr>
<tr>
<td>F606W</td>
<td>20</td>
<td>120</td>
<td>41.7</td>
<td>15.2</td>
<td>0.8%</td>
<td>0.101</td>
</tr>
<tr>
<td>F814W</td>
<td>84</td>
<td>504</td>
<td>176.6</td>
<td>57.0</td>
<td>0.4%</td>
<td>0.090</td>
</tr>
</tbody>
</table>

On January 15, 2015, midway through the FF observing campaign, the ACS team began adding LED post-flash to its calibration darks in order to preserve warm pixels previously lost during readout due to poor charge transfer efficiency (CTE, Ogaz et al. 2015a). This allows for a better dark calibration in the vicinity of warm pixels and their trails, and it also allows for improved data quality flagging in the long Frontier Fields exposures, which have a similar non-zero sky background. The first three cluster parallels were therefore calibrated using the standard (un-flashed) dark reference files and the last three using the new ‘flashed’ reference files, as indicated in column 4 of Table 1.
The mean sky background in F435W is listed in column 5 for each target. This value is not impacted by the type of dark reference file, since the additional flashed background is removed from the darks prior to delivery. The ecliptic latitude of each parallel field is given in column 6, where the three targets furthest from the ecliptic (30 degrees or more) have the lowest sky background. This is illustrated in Figure 1, which plots the mean sky background versus the absolute value of the ecliptic latitude.

![Graph showing mean sky background vs. ecliptic latitude](image)

*Figure 1. The mean sky (electrons/second) in F435W versus the absolute value of the ecliptic latitude for each of the observed parallel fields, where the error bars represent the dispersion in the measured sky values. As expected, larger sky backgrounds are observed for targets closer to the ecliptic. Note that all of the FF clusters were selected to be far from the plane of the Galaxy, such that extinction effects are minimal.*

**III. Analysis**

The raw FF data were processed using the standard calibration pipeline, CALACS. In addition, new software was developed to correct for small-scale artifacts not removed by the dark subtraction step. This new “self-calibration” procedure (Anderson, 2013) is useful for programs with many dithered frames of the same target obtained at the same orientation. Objects that move with the dither are considered to be real astronomical sources, and those that do not are assumed to be artifacts. The software is able to identify warm pixels which may be trailed away in the dark frames due to poor charge-transfer efficiency (CTE) and to flag residual CTE trails behind bright cosmic rays. As a result, self-calibration removes coherent residual structure, reduces the total noise, and increases the overall depth of the combined ACS mosaics (Ogaz et al. 2015). This is especially important for observations with low sky background, either due to their position at high ecliptic latitude or due to the choice of filter bandpass. For example, the mean sky background from Table 2 is ~5 times lower in F435W compared to F606W and F814W.
Self-calibration produces a unique ‘delta-dark’ correction for each target field, which is then subtracted from each exposure prior to flat fielding. An example of this dark correction frame is shown in Figure 2 for F435W observations of the MACS1149 and MACS0717 parallel fields. These two targets are a similar ecliptic latitude and have comparable sky backgrounds (see Table 1), but the later target was calibrated using the newer flashed darks. In both cases, maximum correction to the dark image increases closer to the chip gap where CTE effects are the greatest. For MACS1149, the correction is as large as ~2 electrons for a typical 1300 second exposure, or ~0.0015 e/sec. This is approximately 6% of the typical sky background for this target. The maximum correction for MACS0717, on the other hand, is less than half that of MACS1149 at ~0.8 electrons for a 1300 second exposure, or ~0.0006 e/s, which is about 2% of the typical sky value. The delta-darks derived from self-calibration demonstrate the improvement in ACS data products when calibrated using flashed darks. This can be important for smaller observing programs where self-calibration is not possible due to the limited number of frames.

Figure 2. F435W delta-dark derived from self-calibration for a typical 1300 second exposure of the MACS1149 (left) and MACS0717 (right) parallel fields, which have similar sky backgrounds. The bottom panels show an average projection across columns indicated in the red rectangle. The maximum correction (in electrons) near the chip gap is larger for observations calibrated with un-flashed darks (left) compared to those calibrated with flashed darks (right).
Since the calibrated *flc.fits data products have already been divided by a flat field during processing by CALACS, any remaining spatial residuals observed in the sky background correspond to a ‘delta’ correction to the current pipeline flats, assuming the response in a given filter is not dependent on the color of the stimulus. The current set of flats used by the pipeline for this analysis for F435W, F606W, and F814W are qb12257gj_pfl.fits, qb12257sj_pfl.fits, and qb12257pj_pfl.fits, respectively. As shown in Table 2, the total sky background (zodiacal + earth-shine) decreases at bluer wavelengths, so the F435W data will highlight not only errors in the flats, but may also be sensitive to any detector artifacts not fully corrected by CALACS during pipeline processing.

The FF parallel fields are relatively sparse and devoid of extended objects, so sky flats may be derived by simply masking sources, normalizing the background, and then stacking the exposures of all six parallel fields by filter. Had the flat fielding been perfect, the residuals would be spatially flat with a mean value of unity and with a noise level expected from Poisson statistics, assuming a nearly uniform sky background. The main cluster fields were not used in this study in order to avoid contamination from the diffuse cluster background, which varies across the detector field of view and which is likely to be a different color than the sky.

To compute sky flats for each filter, the individual (*flc.fits) exposures of each parallel field were aligned using the DrizzlePac task TweakReg, using an initial set of SExtractor source catalogs which were provided as input for object matching. The image headers were then updated to correct for any small offsets in the world coordinate system due to FGS pointing errors. Next, AstroDrizzle was used to combine the mosaics for each of the six parallel fields. Figure 3 shows the combined mosaics in three ACS broadband filters for the adjacent ‘blank’ region just south of MACSJ1149.5+2223, which was observed in parallel while WFC3/IR was pointed at the main cluster. The display has been stretched to highlight variations at the level of –5 to +10 times the standard deviation of the background, which is ~0.0016 e/s for F435W and F814W, ~0.0032 e/s for F606W.

SExtractor was used to create segmentation maps for each drizzled mosaic in order to mask pixels associated with astronomical sources. These maps were smoothed with a Gaussian filter to ‘grow’ the object masks in order to exclude the extended faint wings of background stars and galaxies. After carrying out a series of tests to examine the behavior of different smoothing sizes on the image properties, a FWHM of 0.60” (20 pixels for the mosaics drizzled at a scale 0.03”/pixel) was chosen as the smoothing size that best captured faint extended emission around objects while also not smoothing smaller sources too much. The masks were then ‘blotted’, or reverse drizzled, from sky coordinates to the original detector image reference frame to create a set of masks corresponding to each input calibrated *flc.fits image. More detail on the FF data pipeline used to calibrate and align these images and to generate the object masks is available in Koekemoer et al. (2018, in prep).
Figure 3: Combined mosaics of the MACSJ1149.5+2223 parallel field. The drizzled products are oriented with North up, and the blue arrows indicate the direction of the x/y axes in the original ACS/WFC detector coordinates.
The object masks were combined with data quality masks from each individual frame in order to include additional flagging of cosmic rays, satellite trails, optical ghosts, and scattered light from bright stars just outside the field of view. The result is a set of images where ‘good’ pixels correspond to regions of the detector with clean sky background and ‘bad’ pixels are set to a value of -999 for easy rejection. Figure 4 shows an example of a single calibrated *flc.fits exposure and its associated mask. Typically, ~10% to 20% of pixels in a given calibrated exposure were masked, with more pixels masked at longer wavelengths where the background galaxies are generally brighter and more extended in size. While this is a significant fraction of the available pixels, the random distribution of sources in each parallel field, combined with a large number of independent datasets, ensured good coverage over the entire WFC array.

For optimal scheduling, the individual observations in a given ACS filter vary by ~30% in the commanded exposure time. Even for exposures of the same length, the measured background varies by nearly a factor of 2. For this reason, each of the masked *flc.fits images was then normalized by its mean sky value (in electrons), as computed directly from the masked frames. Finally, observations from all six parallel fields were averaged for each of the three broadband filters, rejecting any masked pixels. For F435W, the set of masked images were also combined using inverse-variance weighting, based on the standard deviation of the background in each frame, but the resulting sky flat was nearly identical to the one computed from a simple average.

Figure 4: (Left) A single calibrated ACS exposure, jcdu15hjq_flc.fits, observed in F814W from the MACSJ1149.5+2223 parallel field (left). The combined mask associated with this exposure (right), where white pixels were set to 1.0 and black pixels, corresponding to astronomical sources, cosmic rays, satellite trails, and other artifacts flagged in the data quality array of the image, were set to 0.0.
IV. Results

The properties of the combined sky flats are summarized in Table 2, which lists the cumulative sky background in units of $10^3$ electrons and the associated average Poisson error, assuming uniform depth across the field of view. With a total signal of $\sim$57,000 electrons, the F814W filter has an rms error of $\sim$0.4% per pixel, nearing the accuracy of the ACS flats derived from ground test data which had $\sim$100,000 electrons and an error of 0.3% per pixel (Bohlin et al. 2001). In reality, the pixel-to-pixel rms of the sky flat varies over the field of view due to source masking in each of the six parallel fields, and more observations would need to be stacked for the sky flat to rival accuracy of the ground flat. An initial attempt at making a P-flat for the F435W filter, based on many co-added sky frames, is described in Lucas & Grogin (2016). A summary of that work and a comparison with the results from this study is highlighted in the Appendix of this report.

To look for any large-scale correlated structure, indicating the need to apply a correction to the current set of reference files, the sky flat residuals were smoothed with a circular median filter of radius 8 pixels, rejecting any values less than 0.95 and greater than 1.05. These cutoffs were used to exclude pixels affected by data quality issues and were determined by visual inspection of the image histograms. The smoothed sky flat residuals are shown in Figure 5 (right) with a display range from 0.97 to 1.03. For comparison, the current set of flat reference files are shown in the left panels of Figure 5, with a range from 0.90 to 1.10.

In both F606W and F814W filters, the sky flat shows a large ‘donut’ or ring-shaped residual similar in shape to the flat field quantum efficiency (QE). The white ring seen in F606W is $\sim$1% higher than the adjacent darker regions which have a mean value of 1.0. This ring correlates with regions of relatively high QE in the flat. Conversely in F814W, the same ring is dark in the residual image with a mean value of 1.0, and the surrounding pixels are $\sim$1% higher. This dark ring correlates with regions of lower QE in the F814W flat. While a hint of this shape is apparent in F435W (e.g. a dark blob just left of the center of the detector), the sky flat appears to be dominated by detector artifacts. A discussion of the residuals in this bluer WFC filter is deferred to Section 5.

The ‘donut’ pattern in the flat field closely maps the WFC detector thickness, which was derived from fringe flats during ground testing (Walsh et al. 2003). The total range in thickness varies by $\sim$4.5 microns across the detector and is reproduced from Krist (2003) in Figure 6. An excerpt from that report states:

“At wavelengths below $\sim$700 nm, the QE is inversely proportional to the CCD thickness - it is high where the chip is thin and low where it is thick. This may indicate the incomplete removal of “dead” material in the thicker regions of the chip during the thinning process. Unproductive absorption of short wavelength photons would lower the QE in these areas. As the wavelength increases, a larger fraction of photons is absorbed deeper in the CCD. At $\sim$700 nm, photons can pass completely through the detector and are reflected or scattered back into the device by the back side. This increases the path length and thus chances for productive absorption. In F755W, the QE is relatively uniform over the field because the thickness variations are a small fraction of the
absorption path length. At long wavelengths, however, the pattern seen in the blue inverts, so that thin regions have the lowest relative QE. Here, the path length is insufficient to absorb all of the photons, some of which are reflected off the backside of the CCD and out of the front of the detector.”

Figure 5. (Left) The flat reference files (PFLTFILE) for F435W, F606W, and F814W displayed on a scale from 0.90 to 1.1. (Right) Sky flat residuals in the same three filters, smoothed with a circular median filter to highlight low-frequency structure. In the F435W filter, the observed residuals are ±2.0%. The F606W and F814W sky flat residuals are much smaller at ±0.5%.
These results suggest that the current set of flat field reference files for F606W and F814W (created in mid-2006) are still accurate to within the calibration goal of ~1%. Small differences in the measured response may in fact be due to slight differences in color between the sky background and the 47 Tucanae calibration field used to derive the L-flat corrections, rather than true errors in the flat itself.

V. F435W Sky Flat

As discussed in Section 3, the total sky background is significantly reduced at bluer wavelengths, so spatial residuals in the F435W sky flat will reflect not only errors in the flat field, including any possible color-dependency, but may also highlight detector artifacts which were not fully corrected by CALACS during pipeline processing. These could include an imperfect bias, dark, and/or pixel-based CTE correction.

The sky flat for this bluest ACS/WFC filter is shown in the top right panel of Figure 5. In the central region of the detector, where the detector QE is the lowest at short wavelengths, a dark blob is seen just left of center which is ~1% lower than the adjacent pixels. This is consistent with the sky flat residuals for the F606W and F814W filters, where pixels with lower QE produce correspondingly low residuals in the sky flat.
In addition to this pattern, a constant offset can be seen in the sky flat at the boundary of amplifier B. This can be attributed to uncertainties in the bias level subtraction due to random variations in the difference between the leading physical overscan and the bias level in the active imaging region of each exposure. If these offsets were constant, a full frame bias subtraction would remove any differences. In practice, the offsets show random variations ~0.3 DN that may be caused by interference between the WFC integrated electronics module and the telescope and/or other science instruments (Sirianni et al. 2003). The accuracy of the bias level subtraction in a single quadrant is limited by this random effect. As a result, background levels may appear discontinuous across the boundaries of adjacent image quadrants after processing with CALACS. The FF data were not manually corrected to account for amplifier offsets and, in the case of low sky background, these residual features are often very noticeable in the single calibrated exposures, as well as in the combined sky flat.

Another source of uncertainty in the calibration is the pixel-based CTE correction applied in the ACS pipeline, especially for faint sources such as warm pixels at low background levels. To understand whether any residual CTE effects are present in the sky flats, the F435W observations were broken into two equal samples of 108 exposures each (3 targets per sample, with 36 frames per target). As discussed in Sections 2 and 3, the ACS team began adding LED post-flash to its calibration darks exactly midway through the FF campaign. Post-flashing the detector fills in a majority of the WFC charge traps by providing a higher background level, which prevents the warm pixels in being trailed out of existence in the dark. Post-flashing also allows the CTE-correction software to provide a more accurate reconstruction of the true dark current. The FF mosaics which were calibrated using post-flashed darks, but without any additional ‘self calibration’, show a considerable reduction in the noise structure of the sky background by properly flagging and correcting for these type of faint detector artifacts.

Figure 7 compares the F435W sky flat derived using only the first three parallel fields (calibrated with un-flashed darks) and the sky flat computed using only the later three parallel fields (calibrated with flashed darks). While the additional self-calibration step should in theory remove any remaining CTE residuals caused by an improper dark subtraction from either of the data samples, this correction is likely imperfect. For example, when comparing the sky flat residuals near the center of the detector where CTE losses are the largest, observations calibrated using the higher fidelity flashed darks (right) reveal a more pronounced residual dark blob at the center of the detector, coincident with the flat ‘donut’ feature where the F435W sensitivity is the lowest. This ‘donut’ is slightly more washed out in the left panel, where a dark horizontal band of low residuals can be seen close to the chip gap where the number of parallel transfers is the largest. This band-like feature is most noticeable on the bottom WFC chip, where the low sky residuals extend ~600 pixels below the gap.
Figure 7. F435W sky flats derived from the first three FF parallel fields, calibrated with the old standard un-flashed darks (left), and from the last three FF parallel fields, calibrated using the newer flashed darks (right).

Figure 8. F435W sky flat derived from the last three FF parallels (left) and the weight image of the combined set of dithered 47 Tucanae observations (right) used to derive the 2002 L-flat correction image. Sky flat residuals are systematically 1-2% lower in a rectangular annulus at the outer edge of the detector. The region outside the red box corresponds to portions of the detector with 8 dithered 47 Tucanae exposures or fewer, of a potential 18 exposures in the central region. The flat field reference file may therefore to be less accurate at the edges of the detector.
The F435W sky flat shows a large rectangular-shaped residual at the outer edge of the detector which is ~1-2% lower than the central region. The width of this feature is similar in size to the 9-point dither pattern used to observe the original 47 Tucanae calibration field (Mack et al. 2002). Red circles indicated on the sky flat in Figure 8 (left panel), derived from Frontier Fields data, are 620 pixels in diameter, or 15% of the ~4100 pixel detector FOV. The drizzled weight image for the 18 combined 47 Tucanae exposures is shown in the right panel, where the inner red box is ~4100x4100 pixels in size and the combined frame is ~6000x6000 pixels. The red circles are 880 pixels in diameter, which corresponds to the maximum dither on the sky of ~44” in both x and y. This edge region is ~15% of the size of the combined drizzled image. The axes of the weight image are slightly tilted on the sky due to distortion, which translates into nearly rectangular features in the detector frame of reference. The region inside the red box corresponds portions of the detector with 10 or more dithered exposures of 47 Tucanae. Outside of this box, the flat field may be less accurate than at center of the detector due to fewer total measurements.

Another feature apparent in the sky flat is a horizontal ‘beat pattern’ ~0.5% peak-to-peak, which repeats every ~100 pixels along the y-axis. This is similar in size to the dither pattern used to construct the Frontier Fields mosaics. When ACS was observed in parallel with WFC3/IR, the standard WFC3 “IR-DITHER-BLOB” pattern was used, which performs a ~5” dither along a 42 degree diagonal in order to step across “blobs” of reduced detector sensitivity which are as large as 3.3” in diameter. (McCullough et al. 2014). Because the ACS/WFC and WFC3/IR detectors are oriented 47 degrees from one another on the sky, a 5” diagonal dither in WFC3 translates into a nearly vertical 5” dither or 100 WFC pixels along the ACS detector Y-axis. This large shift allows for full coverage on the sky across the 2.5” CCD chip gap.

In an effort to remove this beat pattern, separate sky flats were computed for each of the four dither positions from each visit, and these were then averaged and smoothed. Similarly, sky flats were computed from the average of images 1 and 2 and also from the average of images 1 and 3. In each case, the horizontal pattern persisted in the residuals. It is worth noting that both the F606W and F814W sky flats exhibit a similar repeating pattern, although it is much smaller at ~0.1%. If sky flat correction images were to be delivered as official ACS reference files for these two filters, this pattern would need to be corrected or else smoothed out. For the purpose of this study, which is to validate the accuracy of the pipeline flats to ~1%, we simply note that it exists. One possibility is that the pattern could be an artifact of the self-calibration process, which assumes a perfect flat field calibration.

For the F435W filter, the sky flat is not useful as a correction image because it contains too many detector artifacts. These effects are superimposed on any true flat field residual, which is assumed to resemble the donut pattern in the flat, if similar to what is seen for the F606W and F814W filters. The flat field for F435W may in fact depend significantly on the color of the stimulus, as described in Section 6, which describes the photometric repeatability red and blue standards measured across the WFC array.
VI. Point Source Photometry

To verify the spatial stability of the ACS/WFC sensitivity, Bohlin et al. (2017), hereafter B17, compare relative photometry in a large 1” (20 pixel) aperture for two bright HST standards stepped across the detector in the F435W and F814W filters. The authors find that after correcting for sensitivity losses linearly correlated with total distance (X+Y pixels) from the readout amplifier, the measured flux in F814W is consistent across the array to within ~1% for both a blue standard star (GD153) and a red standard star (KF06T2). The authors overplot the sky flat residuals derived from this study onto the a map of the photometric residuals of the two stars and show that two independent methods produce results consistent to within ~0.5%. In the majority of cases, the sky flat residual lies midway between the photometric residuals computed for the red and blue stars.

One exception is at the top edge of the detector, where the F814W sky flat residuals are ~1% higher than the photometric residuals. Rather than indicating an error in the flat, these residuals may instead be a result of scattered light from bright sources just outside the field of view in the Frontier Fields data. As discussed in Section 4, the sky flat residuals in F814W (and similarly in F606W) may be a result of slight differences in color between the sky and the slightly bluer average population of stars in the 47 Tucanae calibration field used to derive low-frequency corrections to the ground flats.

For the F435W filter, B17 shows that the photometric stability of the red standard is better than ~1%, with the exception of the lower right corner of the detector. For the blue standard, the photometric residuals are up to ~3% fainter than expected, suggesting that the F435W flat may have a significant color term. The authors fit a 2-D cubic polynomial to the spatial residuals and provide a ‘delta’ flat field correction for sources similar in color to GD153. For stars of intermediate spectral type, a linear interpolation between the delta flat for the blue and red stars is provided.

An indication of this color dependence was noted by Bohlin et al. (2001), based on the ratio of a monochromatic 4300Å flat to a white-light tungsten flat obtained from ground test data. The ratio (reproduced in Figure 9, left) shows low-frequency structure attributed to differential variations in sensitivity with the spectral flux distribution of the source. Residuals exceeding 5% were found in the central ‘blob’ of the flat field where the CCD is the thickest. The authors thus advised users to exercise caution when performing relative photometry over the large WFC field of view in this filter. The flat ratio is notably similar in shape and intensity to the delta-flat correction derived by B17 for the blue white dwarf standard GD153 (reproduced in Figure 9, right).

In-flight corrections to the ground flats (Mack et al. 2002) were based on photometry of 47 Tucanae, an old globular cluster with a predominantly red population, so the 1% photometric repeatability of the red HST standard by B17 makes sense, if there is indeed a color-dependence in the detector response at short wavelengths. To verify this effect, L-flats could be recomputed from the original 47 Tucanae dataset, first splitting the sample into two separate populations based on color. This would allow for a higher-fidelity correction image for stars of different spectral type than the low-order polynomial fits.
provided by B17. This would also eliminate any systematics in the flats due to color gradients in the 47 Tucanae calibration field, which is ~6’ west of the cluster center. For example, it is possible that the rectangular feature at the outer edge of the F435W sky flat may disappear if only stars of a similar spectral type were used to derive the L-flat.

Curiously, the F435W point source photometry does not show similar large residuals at the edges of the detector. While the L-flat correction is based only on dithered 47 Tucanae observations obtained at a single orientation in 2002, many more observations of this cluster are now available at a range of orientation values, via the ACS/WFC sensitivity monitoring program. Increasing the size of the data sample would be useful for computing a more accurate L-flat correction in order to verify whether the large flat field errors at the edges of the detector, as suggested by the sky flats, are real.

Figure 9. The ratio of a monochromatic 4300Å flat to a white-light tungsten flat in F435W (left, reproduced from Bohlin et al. 2001), suggesting substantial low-frequency residuals in the detector sensitivity with spectral flux distribution. The delta-flat correction (right, reproduced from B17) required for a blue sources in F435W based on high signal-to-noise stepped photometry of the white dwarf GD153.
VII. Conclusions

Sky flats from deep FF imaging suggest that the current set of flat fields are accurate to ~1% in the F606W and F814W filters. Constructing an accurate sky flat for the F435W filter is more problematic, since the sky background is much lower at this wavelength and detector artifacts dominate the residuals. Point source photometry of red and blue HST photometric standards positioned across the WFC detector confirms the accuracy of the F814W flat to better than 1%. For F435W, the flat is consistent to ~1% for the red standard, but shows deviations of ~3% across the field of view for the bluer white dwarf standard. Bohlin et al. (2017) provide a delta-flat correction for this filter in order to achieve the goal of 1% precision for all spectral types. A reanalysis of L-flat correction in this filter, first splitting the 47 Tucanae stars into separate populations by color, would confirm whether a separate flat field is required for sources of varying spectral type.

Acknowledgements

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Appendix: Comparison with Sky Flats from Lucas & Grogin

The ACS team conducted a prior, independent study to compute sky flats for the WFC, with the goal of validating both the pixel-to-pixel sensitivity and any low-frequency residuals (Lucas & Grogin, 2016, hereafter LG16). If sufficient signal-to-noise was achieved, these sky flats would replace the current set of reference files used in the pipeline. In contrast, the Frontier Fields sky flat study was intended only to estimate any low-frequency residuals in the current flat calibration, due to their limited depth.

The initial LG16 study was limited to the F435W filter, which is a popular choice in many deep extragalactic surveys. When searching for archival datasets to combine, only observations after Servicing Mission 4 (May 2009), with exposure times greater than 800 seconds and with a gain value of 2.0 were selected. Each of the ‘empty’ extragalactic fields was visually confirmed to be free from extended nebulosity, large galaxies, or extremely bright stars with extended diffraction spikes or optical ghosts. The later constraint was made to avoid possible scattered light of a different color than the sky background. For similar reasons, observations galaxy clusters were avoided in order to avoid contamination from intracluster light.

The selected datasets came from a small number of programs, which are listed in Table 3. These include only the first three of the six Frontier Fields parallel fields due to an additional requirement by the authors to use only datasets calibrated with un-flashed darks (eg. prior to January 15, 2015). At the time of the LG16 study, this excluded the MACSJ0717.5+3745 parallel field which contained several bright stars and a large galaxy. This also excluded the Abell S1063 and Abell 370 parallels which were not observed until the spring and summer of 2016, respectively. (These later targets were calibrated using flashed darks.) Parallel observations from the GOODS UV Legacy Fields (program 13872) contributed significantly to the sample, with 114 frames, as did parallel observations from the UV UDF (program 12534), with 48 frames, although not all images in either program were deemed ‘acceptable’. In total, 274 datasets were selected from 6 programs to produce a cumulative signal of ~8600 electrons and an rms ~1.2%, in accordance with expectations from Poisson statistics.

Table 3. Archival programs used by Lucas & Grogin (2016) to build an F435W sky flat. The FF parallel data used in this study is marked with an asterisk.

<table>
<thead>
<tr>
<th>PI</th>
<th>Proposal ID</th>
<th>Target</th>
<th># Pointings</th>
<th># Images</th>
</tr>
</thead>
<tbody>
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<tr>
<td>Teplitz</td>
<td>12534</td>
<td>UV UDF Parallel</td>
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<td>48</td>
</tr>
<tr>
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<tr>
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<td>Oesch</td>
<td>13872</td>
<td>GOODS UV Legacy Parallel</td>
<td>6</td>
<td>114</td>
</tr>
</tbody>
</table>
To mask sources in the images, SExtractor was run in an aggressive ‘hot’ mode to generate segmentation maps down to the level of the background noise. The segmentation masks were then smoothed using a 10x10 pixel boxcar in order to grow the masks. Each mask was then combined with the corresponding image data quality array using a ‘logical OR’ combination in order to reject cosmic rays and detector artifacts such as bad columns.

The ACS pipeline software task **acsrej** was used to combine the masked frames, weighting all exposures equally. Due to memory issues, it was not possible to combine all 274 images in one pass. Instead, the images were split into 4 groups of similar images from the same visits and scenes. However, visual inspection showed that many artifacts still remained in the combined sky flat. Using a different approach, the first image from each group was combined into a single product, the second image from each group into a second product, and so on, in order to mitigate residuals from sources in any one group of images. The final combination of these sub-group image stacks resulted in an overall cleaner sky flat image with fewer artifacts.

Some artifacts remained, however, and these seemed to be tied to specific features in several fields, especially a large galaxy in the UV UDF parallels. To address this issue, additional smoothing using a 100x100 pixel boxcar was performed on portions of the mask containing the galaxy. For cosmetic reasons, some additional clipping was done on some other small artifacts in the final image which seemed to visually stand out in the combined flat.

A comparison of the sky flat derived from FF parallel data (left) with the sky flat from LG16 (right), is shown in Figure A1, where both are displayed with a range from 0.97 to 1.03. The ratio of these two flats is shown in Figure A2, along with a vertical projection across the detector. The two independent products are remarkably similar at a level of ~0.5%, except at the center of the detector in a horizontal band near the chip gap. In this region, CTE artifacts are present at a level of 1-2%. These features are likely due to the criteria by LG16 to select only datasets calibrated with un-flashed darks. At low background levels, many warm pixels are trailed out of existence in the dark calibration frames frames due to poor charge-transfer efficiency. The FF sky flats, on the other hand, include a delta-dark correction derived from self-calibration, as described in Section 3 and shown in Figure 2.

For the Frontier Fields, a 1300 second exposure produces an average sky background ~30 electrons in F435W, and the delta-dark correction is between 1 and 2 electrons. Between May 2009 - Jan 15, 2015, warm pixels flags were set in the image DQ arrays for pixel values between 0.04-0.08 e/s (Ogaz et al. 2015a). For a similar 1300 second exposure, this corresponds to a range of 52-104 electrons in the warm pixel, with the charge in CTE tails declining exponentially along the column as the charge is read out. For warm pixels at this signal level, which are at least 1500 pixels from the readout registers, the first upstream pixel contains ~8% of the signal in the warm pixel, the second pixel contains ~4.5%, and the third contains ~3%, declining to ~1% by the eighth pixel (Anderson & Bedin 2010). This effect is ~1 electron for a 100-electron warm pixel, equivalent to the typical delta-dark correction from self-calibration.
In Figure 7, a comparison of the 2 sets of F435W sky flats, one calibrated with un-flashed and the other with flashed darks, is based on self-calibrated data, where a separate delta-dark correction was applied for each parallel field. As a result, the large CTE residuals seen in Figure A2 are not apparent in either of the two F435W Frontier Fields sky flats.

Figure A1. A comparison of the F435W sky flat derived from Frontier Fields parallel fields (left) and by LG16 (right). To highlight correlated structure, both products have been smoothed using a circular median filter of radius 8 pixels.

Figure A2. Ratio of the sky flat from FF parallel imaging to that derived by LG16 (left). The ratio is ~1.005±0.005 on average, except near the chip gap which is up to ~2% lower, as shown by a vertical slice along the detector y-axis (right). These low residuals are likely due to CTE artifacts in the LG16 product which are similar in shape to the ‘delta-dark’ seen in Figure 2 and which was removed from each FF parallel field via self-calibration.