

WFPC Flat Field Calibration: Flats and Delta Flats

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Abstract

We review WFPC flat field calibration, as well as the removal of time-dependent effects with Delta flats. Emphasis is placed on various flat fielding problems and their solutions.

I. Introduction

The purpose of flat field calibration is to bring all detector pixels to the same photometric response. The method usually employed is to divide the observed images by exposures of a uniformly illuminated source. While observers will be familiar with this process, there are some differences between flat fielding of ground-based data and WFPC data which should be kept in mind. First, unlike ground-based imaging where one is attempting to flatten a large sky pedestal, most WFPC observations have little or no sky pedestal. Hence, the illumination pattern of the data frames will generally be quite different from those of the flat field calibration images. A related effect is that WFPC images often seem less “flat” after flat fielding, since the uniform readout noise becomes modulated by variations in the calibration flats, even though the flat field calibration is working properly. Another difference is that diffraction effects are much more important for flat fielding WFPC data, as compared to ground-based data. For example, features not in the focal plane (e.g. particles on CCD windows), will not flatten as well as features on the CCDs themselves. Furthermore, differences in color (spectrum) and illumination between the observation target and the flat field light source will be more important.

II. Features and Structures in WFPC Flat Fields

There are many features which appear in WFPC calibration flats. Here we briefly describe some of these, roughly in order of occurrence along the optical path. We will use the WFC F555W calibration flat as an example, since it is one of the more popular filters. Figure 1a shows the entire field of the four WFC CCDs, while Figures 1b and 1c show the center of CCD WF2 at various enlargements. This illustration shows an *observed* flat; the data would be effectively *divided* by this image during calibration. (The actual calibration flats used in the pipeline and CALWFP are inverted, and are multiplied into the data.)

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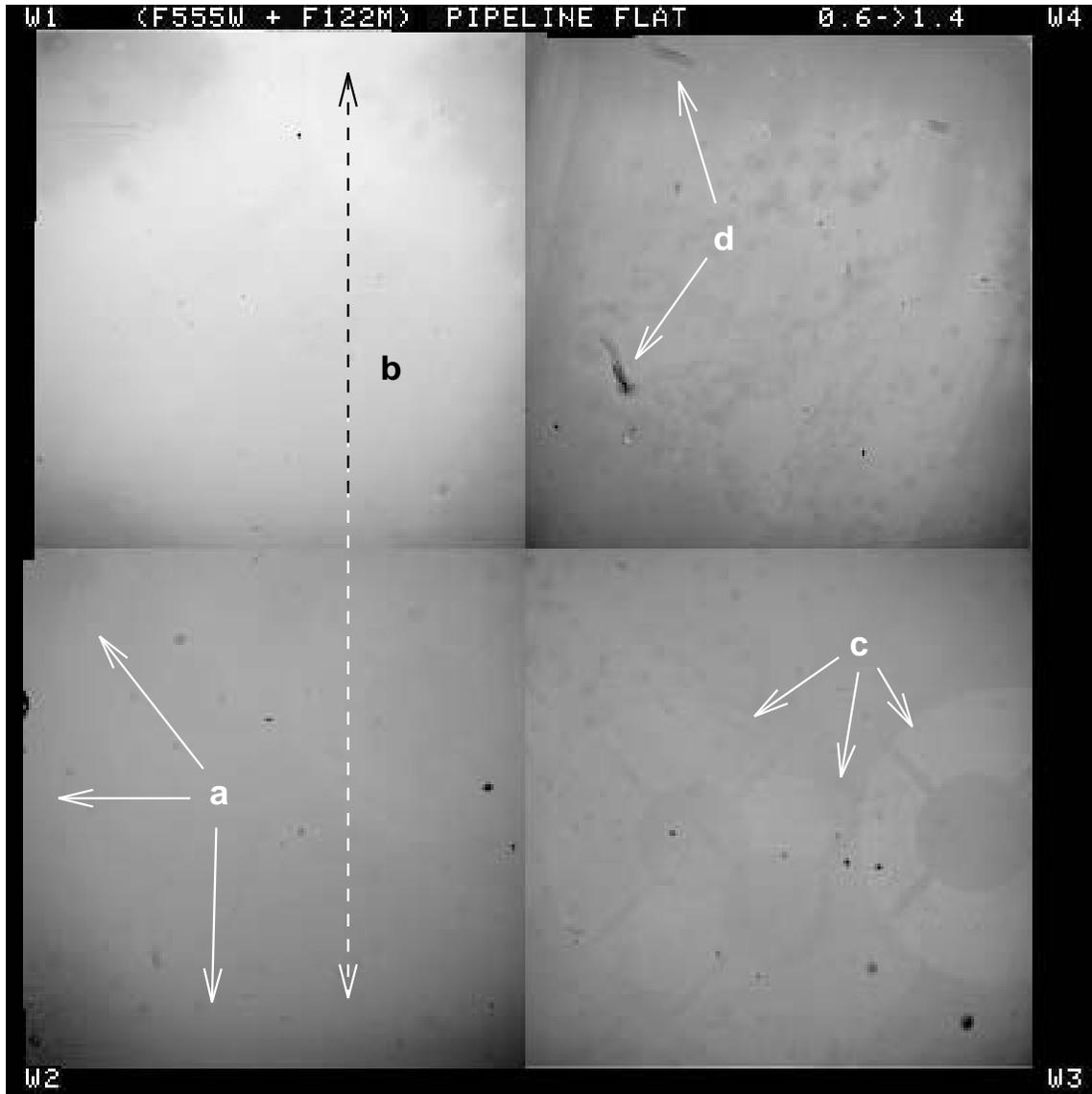


Figure 1a: Flat field used in the calibration pipeline for filter F555W in the WFC mode. The four CCDs have been mosaicked together as they would appear on the sky, and are labeled in their corners. As with many broad-band flats, this one has been observed using the F122M filter to provide neutral density. Labeled features include (a) an intensity fall off at the CCD edges due to vignetting in the camera relay optics, (b) ~30 percent intensity gradient running from the bottom (dark) to top (bright) of the image, which is caused by the neutral density filter, (c) bright “donuts” caused by pinholes in the neutral density filter, and (d) large dust particles on the CCD windows. Display range is from 0.6 (black) to 1.4 (white).

Vignetting in the WFPC relay optics cause the CCD edges to see only a portion of the telescope primary mirror. This causes an illumination drop-off of about 15 percent between the CCD centers and edges, as seen in Figure 1a.

A similar but much smaller effect involves an interaction of the OTA and WFPC obscurations. Near the CCD centers, the OTA spider and WFPC relay secondary support posts have coincident shadows, but at the field edges all seven obscurations appear separately. The amplitude of this effect is only a few percent, and is difficult to discern in the flats.

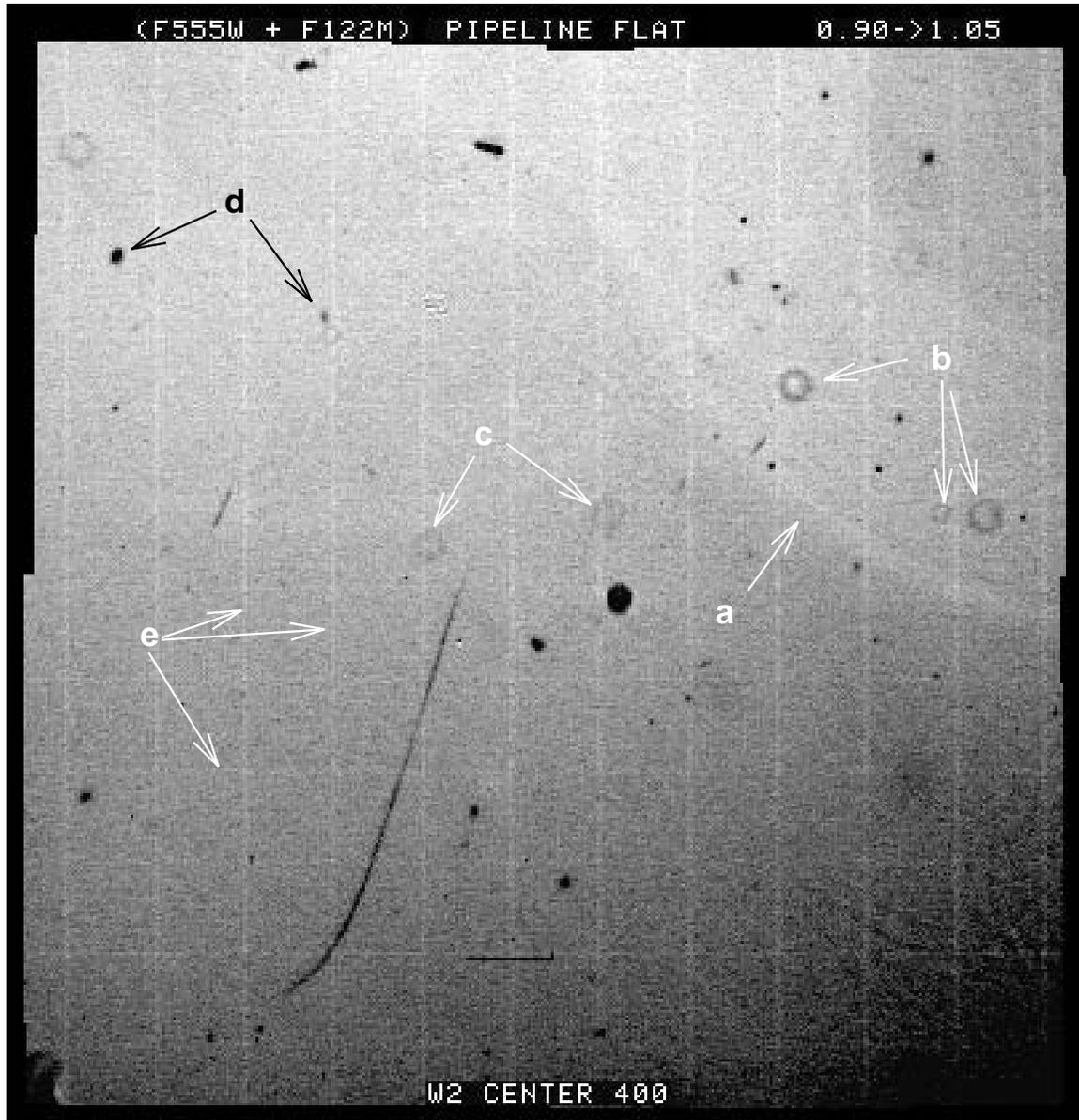


Figure 1b: Enlargement of central 400×400 pixels of WF2 for the image shown in Figure 1a. Labeled features are (a) circular arc caused by pinhole in neutral density filter, (b) small dust spots and (c) measles features on the CCD windows, (d) small dust particles on the CCD, and (e) 33 column / row manufacturing defect in the CCD itself. The display range is from 0.90 (black) to 1.05 (white).

Irregularities in the WFPC filters also contribute features. Perhaps the most important features are those contributed by the F122M filter. The red-leak in this filter is commonly used as a neutral density filter when observing many of the broadband calibration flats (see discussion below). In the case of the F555W calibration flat, the F122M filter contributes a 20 to 30 percent intensity gradient across the four WF CCDs. This is visible as an overall increase in the illumination between the bottom and top of Figure 1a. Small pinholes in the F122M filter also contribute large donut-shaped features which are several percent high. These donuts are images of the WFPC Cassegrain relay pupils.

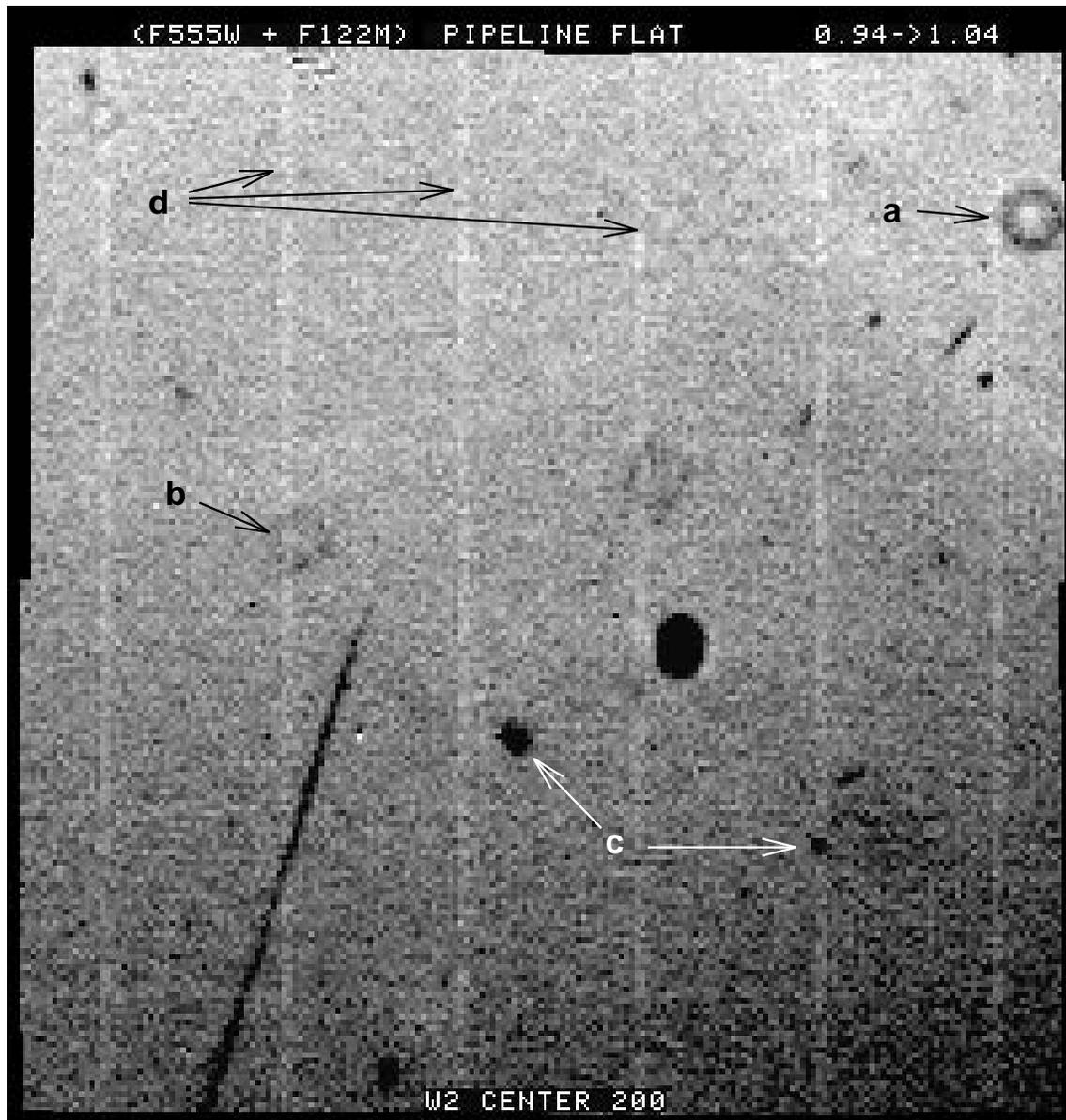


Figure 1c: Enlargement of central 200×200 pixels of WF2 for the image shown in Figure 1a. Labeled features are (a) small dust spots and (b) measle features on the CCD windows, (c) small dust particles on the CCD, and (d) 33 column / row manufacturing defect in the CCD itself. The display range is from 0.94 (black) to 1.04 (white).

Contamination on the CCD windows comes in many forms, and can generally be distinguished from other features as they are slightly out-of-focus. Fibers and dust particles tend to cause large features (e.g. as seen on WF4 in Figure 1a). Low volatility contaminants which remain on the CCD windows after decontaminations cause “persistent measles” (Figures 1c and 2). These appear as bright or dark spots several pixels in diameter, surrounded by concentric bright and dark rings totaling ~ 10 pixels in diameter. The amplitude of these features is typically 1 or 2 percent about the local level, but can reach ± 5 percent. While their exact composition is unknown, they are consistent with particles 10 to 15 microns in diameter.



Figure 2: Illustration of an extreme case of measles. This is an Earth calibration flat for PC8 in the F517N filter. The display range is about ± 7 percent about the mean. From MacKenty, et al. 1992.

High volatility material slowly collects on the windows in a quasi-uniform layer between decontaminations. This material scatters light at short wavelengths, which has the effect of reducing the total illumination (direct + scattered light) at the CCD edges, so that the CCD edges droop in the flat fields. This quasi-uniform layer also alters the properties of the measles and reduces the throughput at UV and blue wavelengths.

Fibers and dust particles on the CCDs themselves tend to be in sharp focus and have a large intensity amplitude (Figures 1b and 1c). Some of these features may also arise on the pyramid mirror, which lies near the OTA focal plane.

The CCDs themselves have sensitivity variations which are apparent in the flat fields. Every 33 pixel columns, there is a pair of columns whose sensitivity is a few percent higher than average (Figures 1b and 1c). A similar pattern occurs every 33 rows. These features result from errors in the CCD manufacturing process. Other features include spots and large regions with anomalous sensitivity due to partial loss of the UV flood, variations in chip thickness, and variations in the Coronene coating.

III. Flat Field Calibration Images

The flat fields currently in use are short exposures of the bright sun-lit Earth. Due to the combination of Earth features and spacecraft motion, these raw Earth-cals often contain patterns of bright and dark streaks which must be removed from the images. This is done using an STSDAS program called STREAKFLAT, which uses many Earth-cals taken at different streak angles to disentangle the flat field pattern from the streaks. Once a suitable destreaked flat is obtained, it is normalized to a mean level of unity, bad areas are clipped out, and the image is inverted using NORMCLIP (also in STSDAS). The resulting calibration flat is then *multiplied* into the data during normal pipeline calibration.

The current library of Earth calibration flats in the Calibration Data Base System (CDBS) were all observed during the baseline epoch between August 1991 and January 1992 (Figure 3). There are two groups of flats, distinguished solely by their origin. The Science Verification or SV flat group contains 36 flats for popular filters, and were supplied by the WFPC Investigation Definition Team (IDT). The second group contains 40 flats for most remaining filters, and were generated by STScI. Besides these Earth-cal flats, there are a variety of other flats available from pre-launch tests, etc. A detailed list of the available flats is maintained on STEIS, and also appears in various WFPC Instrument Science Reports (see references).

While the Earth flats provide the most efficient flat field calibration, they do suffer a number of problems which compromise the final calibration. The most serious problem is that the Earth is too bright, so that either neutral density (ND) filters must be used, or very short exposures (<1 sec) are necessary. The former is problematic, since the ND filters contribute their own pattern and can cause reflections, while short exposures result in very strong streaks which are more difficult to remove from the images. Furthermore, the Earth's albedo is highly variable and unpredictable, so that most of the raw Earth flats are either underexposed or saturated. This low yield makes it very difficult to get enough flats for reliable streak removal. Finally, the Earth color is poorly known and probably does not match that of the celestial targets one wishes to calibrate. Blue oceans, green trees, and red houses are all possible Earth-cal targets.

IV. Internal Flats and Delta Flats

Since the Earth flats only cover a small portion of the camera's history, it is useful to have some other means of checking for, and correcting, time-variability in the flat fields. For this purpose monitoring programs have been undertaken using the internal flat field capability of the WFPC.

Internal flats are exposures taken with faint lamps illuminating the back side of a closed shutter blade. There are two shutters, A and B, either one of which may be in the closed position. The reflectivities of the two are slightly different, so only data from the same shutter should be compared when looking for changes in the flat fields. These internal flats are taken every few weeks in nearly twenty popular filters for each camera. In general, these internal flats are useful only for tracking changes, since their illumination pattern is quite different from that of the OTA, making them unsuitable for use as calibration flats.

WF/PC FLAT FIELD CALIBRATION HISTORY

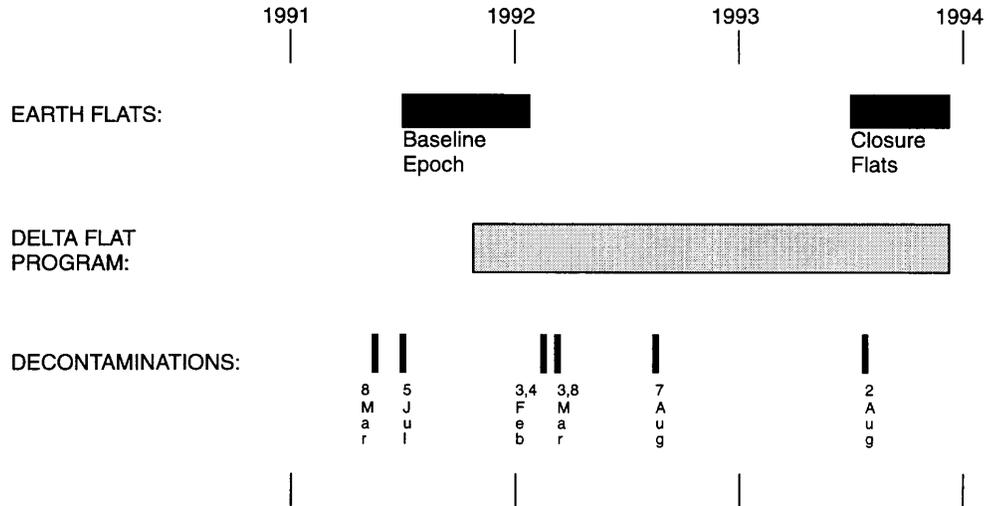


Figure 3: Timeline illustrating the history of the WFPC flat field calibration. The existing Earth calibration flats were observed during the baseline epoch in late 1991 and January 1992. New Earth flats are currently being observed and will be delivered early in 1994 (closure flats). The Deltaflat program spans the interval between the baseline and closure flats. Decontamination events are marked along the bottom of the Figure.

When searching for time variations in the flat fields, it is very helpful to compute ratios of these internal flats. Delta flats are defined to be ratios of single internal flats taken at different epochs (MacKenty and Baggett 1992). Since we are primarily interested in changes since the epoch of the Earth flats, an internal flat from the epoch of the Earth flats, or baseline epoch, is used in the numerator. Hence, Delta flats are computed as:

$$\text{Deltaflat} = (\text{Baseline epoch internal flat}) / (\text{new internal flat})$$

where baseline epoch refers to the period August 1991 to January 1992 (Figure 3). Strictly defined, these are ratios of *single* short exposures, so they tend to contain small numbers of cosmic rays. Average Delta flats are defined to be ratios of *averaged* internal flats. Since the measles tend to be constant between decontaminations, the usual procedure is to average all the internal flats between decontaminations for a given filter. This averaging reduces both the cosmic rays and noise in the images. Some effects, like the CCD edge droop at short wavelengths, do vary between decontaminations, so in some cases it may be better to use the Delta flats rather than the Average Delta flats.

Both types of Delta flats may be used to either check for flatfield variations, or to correct calibrated images. A Deltaflat close in time and wavelength to the science

observation should be used. In the case of a single small target, it may be easiest to merely examine the Deltaflat to insure there are no appreciable changes at the target position on the CCD. In other cases it may be desirable to actually correct the data by multiplying the Deltaflat into the calibrated data. That is:

$$\text{Corrected data} = (\text{Calibrated and flattened data}) \times \text{Deltaflat}.$$

These Deltaflat corrections will often be imperfect, however, since many of the time-variable features arise on out-of-focus surfaces in the cameras. For example, the persistent measles which remained after the February 1992 decontamination result from contaminants on the CCD windows (Figure 2). Because these contaminants are not in the focal plane, the measles pattern will depend on both the illumination and color of the target (diffraction effects, etc.). Unless the target is uniformly illuminated (i.e. planets) one can expect only a partial correction. A general rule of thumb is that the Delta flats will reduce flat fielding errors due to measles by a factor of about two.

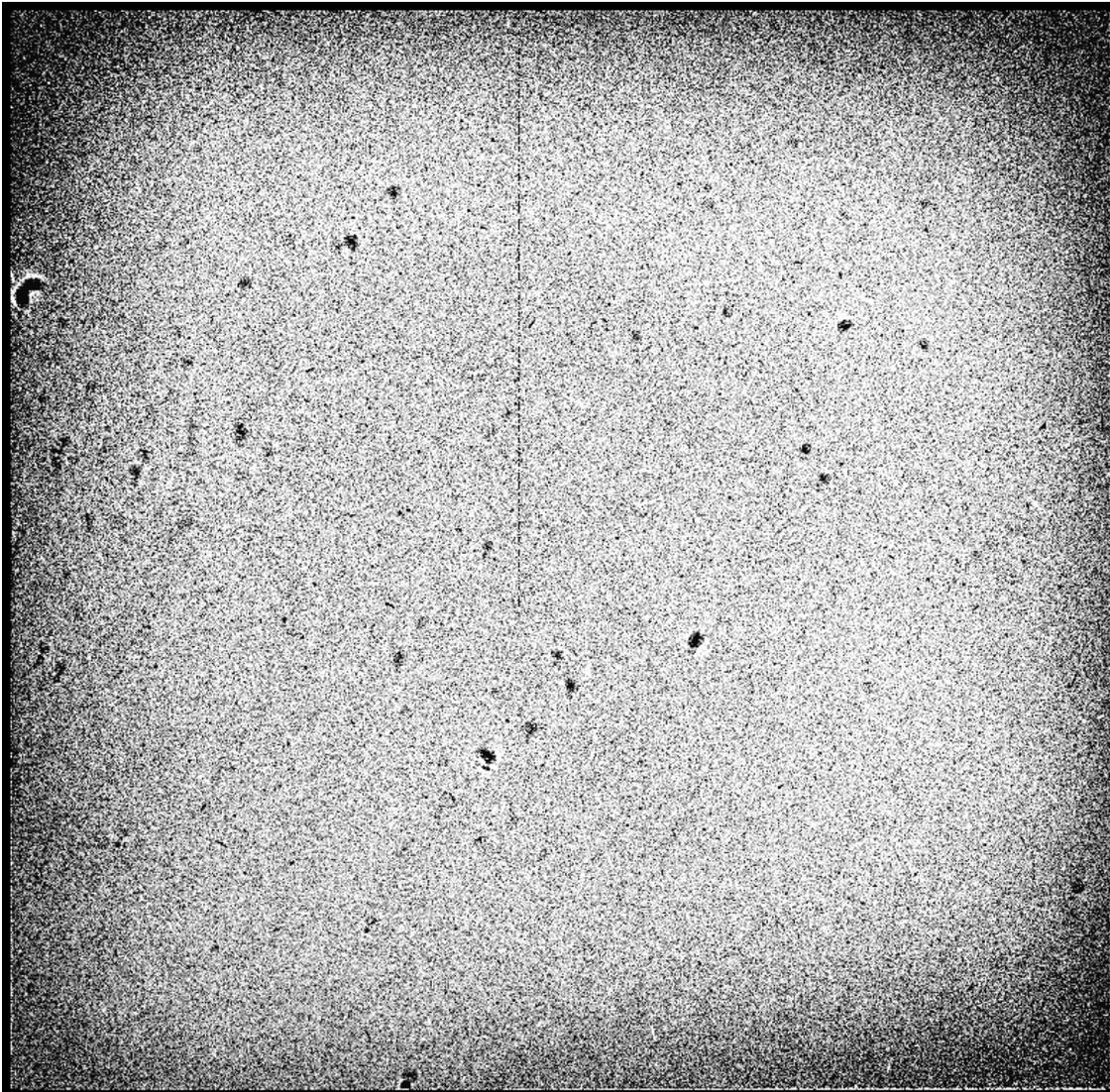


Figure 4: A ratio of PC6 internal flat fields showing the edge droop effect at 439 nm wavelength. Display range ± 2.5 percent about the mean.

Another effect appearing in Delta flats, as well as Earth flats, is the flat field edge droop mentioned in Section 2. The quasi-uniform contaminant layer on the CCD windows scatters light. Near the CCD centers, this scattered light is detected in nearby pixels, so there is little apparent effect on the illumination. But at the CCD edges, the predominant effect is for light to be scattered out of the field of view, causing the edges to be dim or droop (Figure 4). This effect increases gradually between decontaminations as material builds up on the windows, and then largely disappears immediately after decontaminations. The effect is also strongly dependent on wavelength, and is greatest in the blue and UV. For science images the effect will depend on the target illumination pattern. For small stellar targets, there is little droop effect, since the scattered light is lost into the noise of nearby pixels; but for uniformly illuminated targets the effect will be quite similar to that in the flats.

A library of both Delta flats and Average Delta flats is maintained in the CDBS. See STEIS memos for listings of available files (Baggett and MacKenty 1993a).

V. Problems Limiting Flat Field Accuracy — and Solutions

Neutral density filter patterns.

The red leak in the F122M filter has been used as a neutral density filter when observing many of the broad-band Earth flats. Flats observed through the F122M include F555W, F606W, F675W, F702W, F725LP, F814W, and F850LP. It is important to note that intensity variations and patterns caused by the F122M filter *have not been removed from the Calibration Data Base flats!* Since the F122M is not used for science observations, of course, its pattern will corrupt science images during normal calibration.

A solution to this problem is to derive the F122M pattern by taking ratios of flats observed with and without F122M, and then using this derived pattern to correct calibrated science images. The narrow-band filter flats will work best for deriving the F122M pattern, since they have long exposures which minimize streaks and reciprocity effects. For example, we can derive the pattern using F502N flats in the Calibration Data Base System (CDBS), by computing the ratio $(F502N+F122M)/(F502N)$, with the result shown in Figure 5.

Here we see clear evidence for ~25 percent intensity gradient running across all four CCDs. This gradient was first reported by Hester (1992). There are also a number of bright donuts which are caused by pinholes in the F122M filter. These are images of the camera relay pupils; shadows of the Cassegrain secondaries and their three support posts are visible inside each donut. The amplitude of the donuts is about 2 percent, though in some cases they overlap, producing a stronger effect.

This derived pattern can then be used to remove the F122M pattern from calibrated science images. To illustrate this process, we have used the F122M pattern in Figure 5 to correct an F588N flat taken with F122M, and then divided the result by a bare F588N flat. The resulting image, computed as $(F588N+F122M)/(F588N)$ (Fig. 5) is shown in Figure 6. If this process were perfect, we would expect the result to be

perfectly flat. From Figure 6 it is clear that it works quite well. The gradient across the four CCDs has been reduced from ~25 percent to about 4 percent peak-to-peak. The pinhole donuts have been reduced from 2 percent to about 0.5 percent. The fluctuations over the entire WFC field are now about 1.6 percent RMS. We can also begin to see streaks at the 1 to 2 percent level, which are presumably residual streaks from the Earth flats.

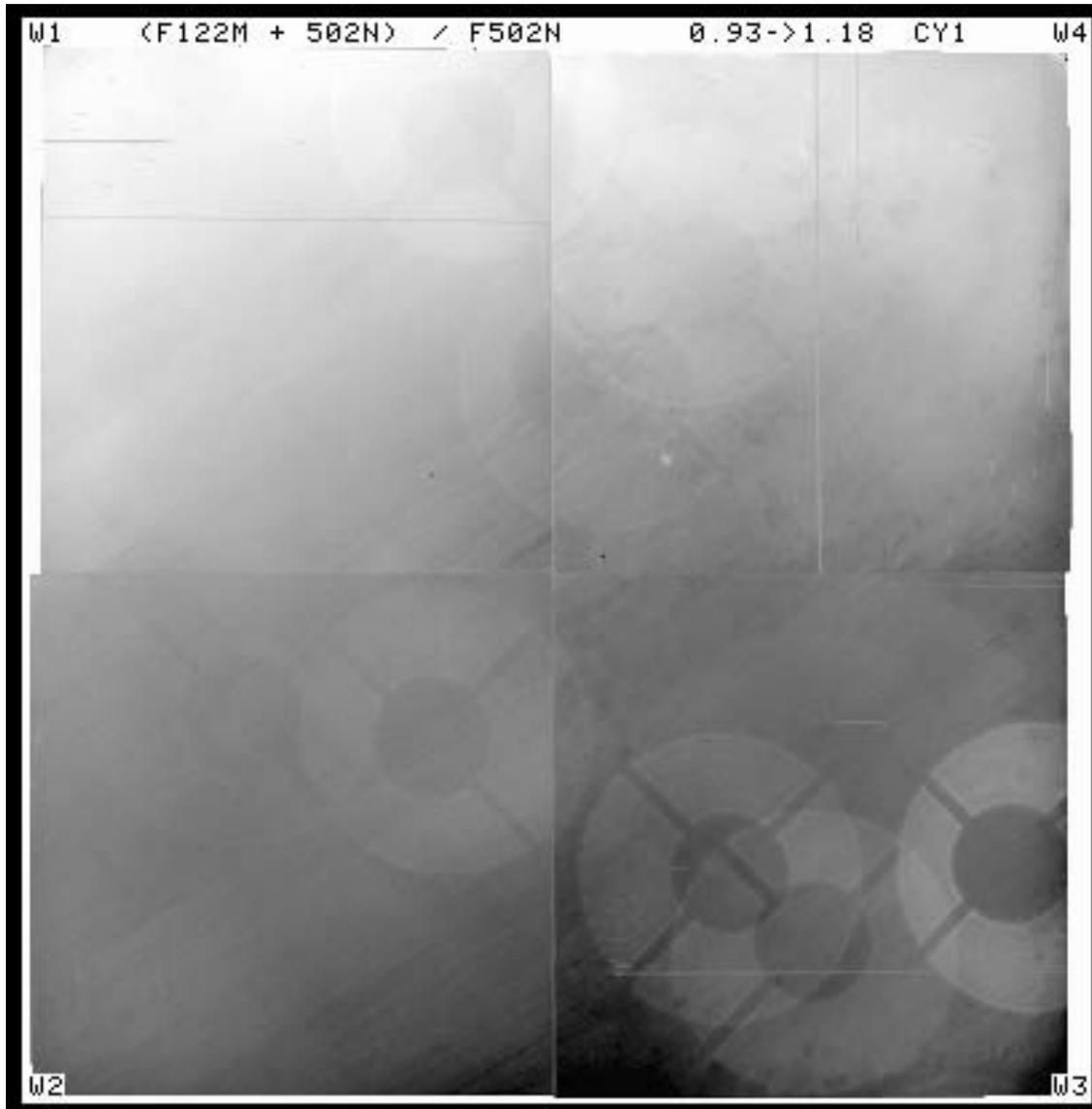


Figure 5: F122M filter pattern derived from existing F502N flats for the WFC. All four WFC CCDs are mosaicked together as they would appear on the sky; the individual CCDs are labeled in the corners. A 25 percent intensity gradient is clearly present, running from the image bottom (dark) to top (bright). There are also a half dozen or so donuts which are caused by pinholes in the F122M filter. The intensity scale ranges from 0.93 (black) to 1.18 (white).

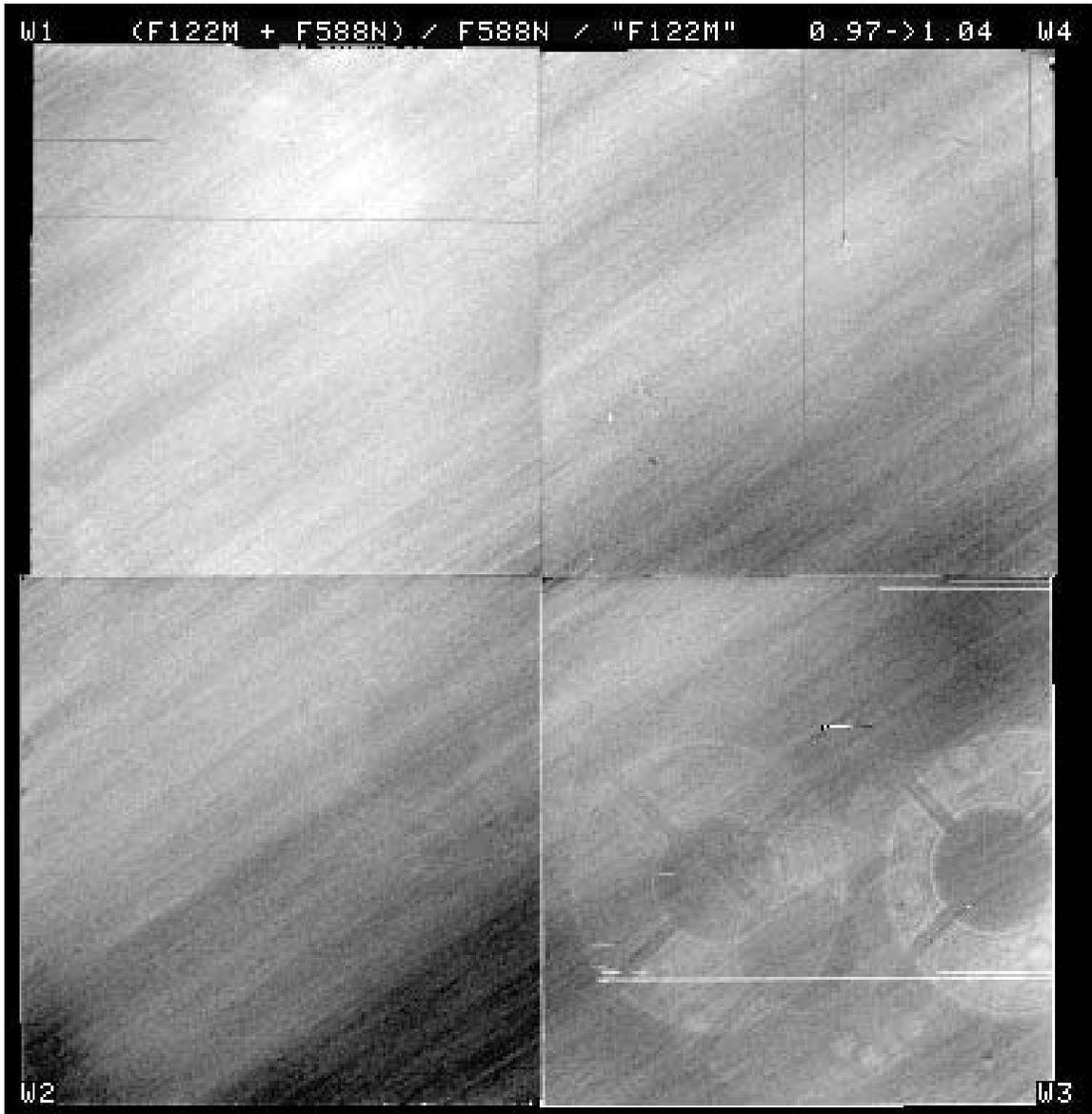


Figure 6: Example of using F122M pattern derived from F502N flat to correct a (F588N+F122M) flat. A 4 percent peak-to-peak gradient remains, as well as 0.5 percent donuts. Residual streaks from the Earth-cals are now evident at the 1 to 2 percent level. The intensity scale ranges from 0.97 (black) to 1.04 (white).

As we will soon see, this procedure does not always work so well. It worked very well for F502N and F588N, because the filters have similar wavelengths, similar constructions, and are in the same filter wheel (wheel 7) within the Selectable Optical Filter Assembly (SOFA).

Another success story is the application of Figure 5 to the F555W broad-band filter flat. We can correct the CDBS (F555W+F122M) flat using Figure 5, and then compare the result against the F555W super-sky flat generated by the Medium Deep Survey group (Ratnatunga, et al., this volume). Our corrected F555W flat and the sky flat are consistent to 2 percent RMS over the central 600×600 pixels of each CCD. (The CCD

edges show slightly larger errors, such that the difference over the entire WFC field is 3 percent RMS.) Again, this works well since F502N and F555W are close in wavelength, and are adjacent in the SOFA (wheels 7 and 9, respectively). Clearly, the materials already exist in the CDBS to largely eliminate the neutral density filter patterns for some filters.

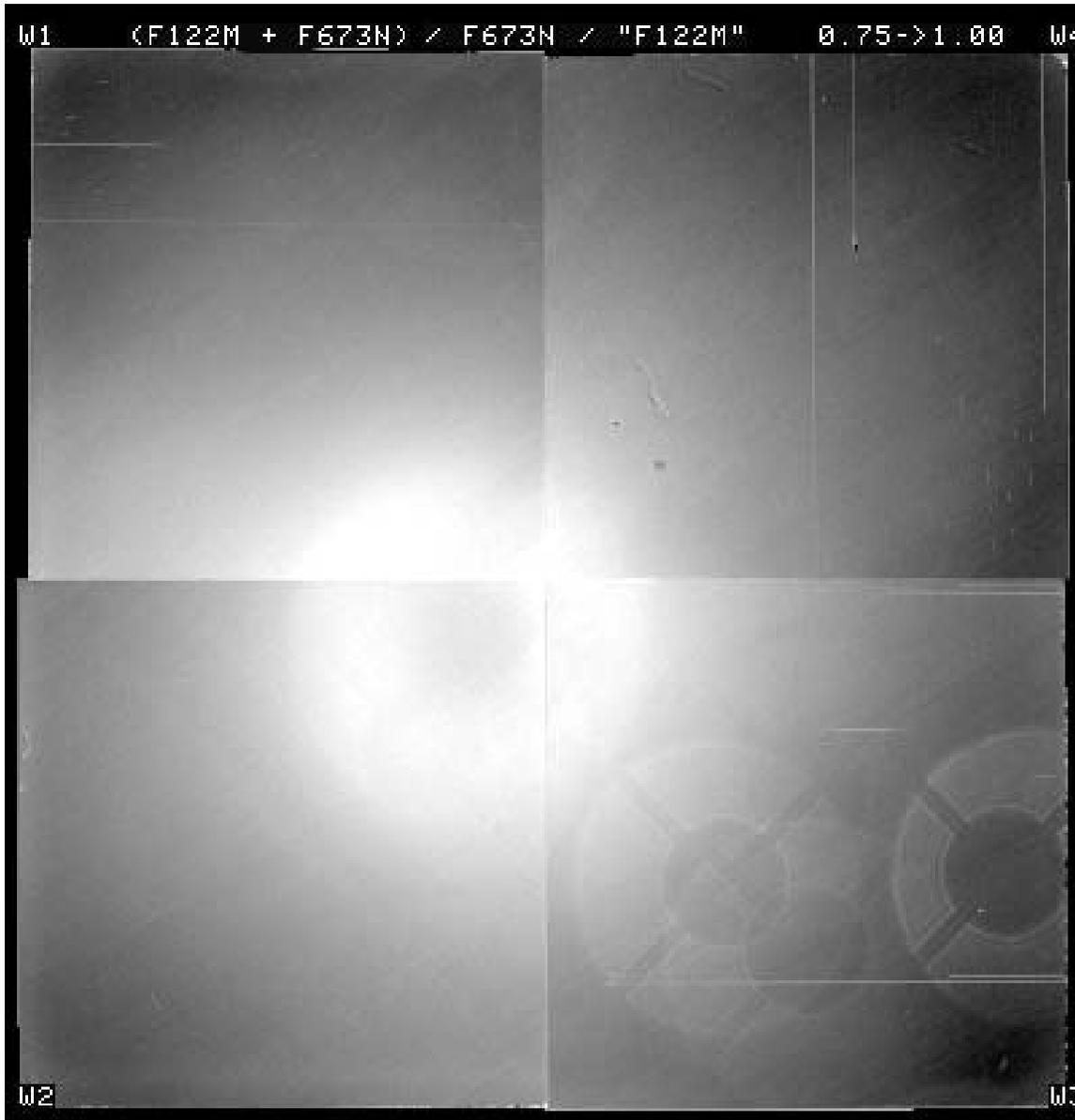


Figure 7: Example of using F122M pattern derived from F502N flat to correct (F673N+F122M) flat. Reflections cause a 30 percent bright spot near the pyramid apex, and hence the procedure fails for F673N. The intensity scale ranges from 0.75 (black) to 1.00 (white).

But things are never so simple as one would like. While we have been successful in deriving the pattern from F502N, and then correcting F588N and F555W with the derived pattern, there are cases where this procedure fails. For example, if we attempt to correct a (F673N+F122M) flat using Figure 5, we obtain the result shown in Figure 7. Obviously this has not worked very well; there is a 30 percent high spot in the center of the image. This high spot results from a reflection off the convex surface of F122M, which is quite strong because F673N is immediately above F122M inside the SOFA (wheels 1 and 2, respectively). This procedure also fails to correct (F889N+F122M). Reflections cause ~25 percent errors, and are due in part to very different wavelengths compared to F502N, different filter constructions (double vs. single interference filters), and different locations in the SOFA (wheel 12 vs. wheel 7). Fortunately, good flats exist for both the bare F673N and F889N filters, so that F122M pattern removal is merely an academic exercise. However, this does emphasize that caution is needed when using the above procedure.

In summary, the F122M filter pattern can be removed to a few percent accuracy using ratios of narrow-band flats. But successful application of this method requires that the filters have similar wavelengths, similar locations in the SOFA, and similar constructions.

Residual streaks in Earth flats.

The STREAKFLAT program is used to remove streaks, which are caused by Earth features, from the flat fields. This program requires about eight input Earth-cals with a wide range of streak angles to successfully remove the Earth features (i.e. reduce streaks below 1 percent level). Due to atmospheric haze the streaks tend to be strongest in the red, and weaker in the blue, so that more or fewer input files might be required at extreme wavelengths.

Long Earth exposures are best, since more averaging occurs along the direction of spacecraft motion. *HST* moves about 40 WFC fields per second, so that little averaging occurs at the shortest ~0.1 second exposures.

An example of a worst case scenario is the F785LP flat currently installed in the pipeline and CDBS. This is a far red filter and 0.1 second exposures were used, so that individual Earth-cals are expected to have very strong streaks. Furthermore, as the header for this flat shows, only four Earth-cals with similar streak angles were used with STREAKFLAT. Given all this, one can expect trouble. As Figure 8 shows, the resulting calibration flat has 15 percent residual streaks which will impose similar errors on the calibrated science data.

Observers can check for similar problems in other calibration flats by examining the headers for those files. The headers list the observed Earth-cals for each flat, and their streak angles.

Trouble is likely if there are only a few input files, or if they all have similar streak angles. Exposure times for the Earth-cals can be checked in either the O/SV Report (Hester 1992) or by querying STARCAT. Exposures much less than 1 second also suggest possible trouble. The ultimate solution is to take more Earth-cals and generate new calibration flats; this work is currently underway.

Jeff Hester's reciprocity effect.

CCD artifacts appear different in very short exposures (<1 second) and very long exposures (c.f. Hester 1992). For example, comparison of 0.1 and 0.3 second flats show 2 percent errors. Hence, short Earth-cal exposures (<1 second) will do a poor job of flattening long science exposures, and should generally be avoided. Again, observers can check the exposure times for the calibration flats as outlined above.

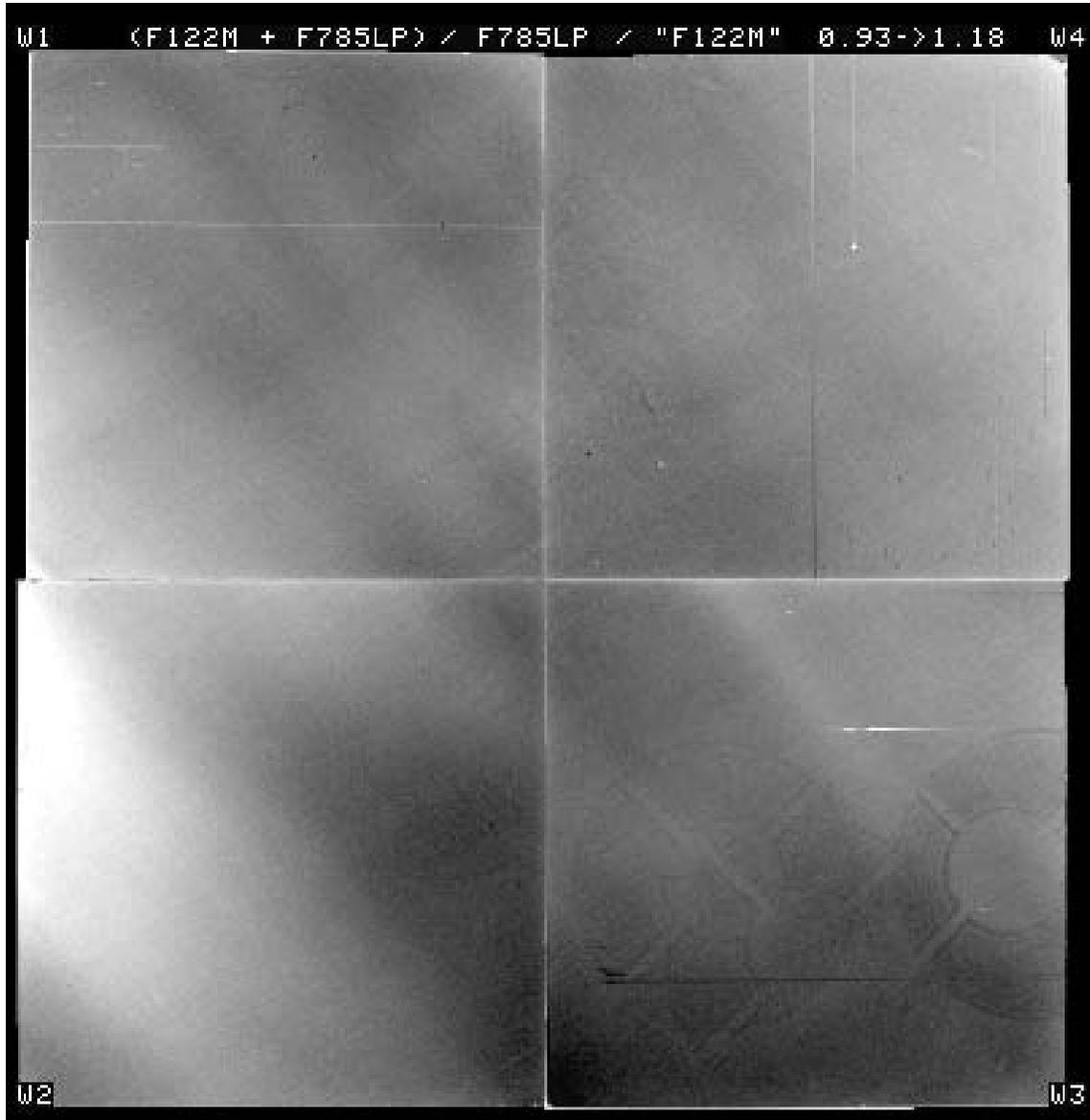


Figure 8: F785LP flat showing strong, broad residual streaks. The F122M pattern has been divided out. The intensity scale ranges from 0.93 (black) to 1.018(white).

Persistent measles.

These features, shown above in Figure 2, appeared in February 1992 and thus are absent from flats currently in the CDBS. They cause ~1 percent errors in the WFC and most of PC6 at F555W. Larger errors of 2 to 5 percent appear in some parts of PC6 and much of the other PC chips, with PC8 being the most serious. Delta flats can be used to locate the measles relative to the targets, and will show whether they will impact the scientific results. The Delta flats can also be multiplied into the science images as a correction; a Deltaflat close in time and wavelength to the observation should be used. In general, these corrections will work best for extended targets, where the internal flats and science data have similar illumination patterns. We may attempt to deliver improved Delta flats for use with the Cycle 3 closure flats.

Scattered light and flat field edge droop.

Earth flats and internal flats taken when the CCD windows are heavily contaminated will show reduced intensity at the chip edges, but most science data (uncrowded star fields, small galaxies) will not show this effect. The intensity error can be up to about 8 percent at the CCD edges at 4000 Å, but will be only about 5 percent at 5500 Å, and less than 1 percent at 8000 Å. Short wavelength images requiring precise flat fielding may be corrected by comparing internal flats at those wavelengths and close in time to the Earth-cal observations and science observations. Some estimate of the effect, and an empirical correction, can then be derived and applied to the calibrated science data.

VI. Advice to Observers

It is important for observers to recognize the characteristics of their own data, so they may concentrate only on those problems which limit their particular science goals. For example, if you have low signal-to-noise data, then you should probably ignore flat field problems altogether. In most cases there is little sky background, so that errors in flat fielding do not affect object detection. So, for faint targets, it is probably more profitable to concentrate on improving bias, preflash, and dark current subtraction.

For high signal-to-noise data involving small targets at the WF2 or PC6 default aperture positions, one can ignore neutral density filter gradients and patterns, as well as edge-droop effects. One should look at both the flats and Delta flats to check that there are no strong features on the target. If several observations with different pointings are available, their results can be compared to check small-scale errors in the flats and corresponding errors in the photometry.

Situations involving wide-field imaging (e.g. star clusters) will be more difficult. Observers should first check whether the F122M filter was used when observing the calibration flat for their data; this can be checked in the STEIS memo on calibration reference files (Baggett and MacKenty 1993b). If the F122M filter was used, they can attempt to remove its pattern using flats nearby in wavelength (e.g. Figure 5). And again, they should look for strong features (dust, etc.) near their targets in the flats

and Delta flats, and perhaps multiply the Deltaflat into their image as a (partial) correction.

We also emphasize that it is important to experiment and try different flat fields, etc. For many filters there are several flats in the CDBS; these are sometimes taken with and without neutral density filters, or use long vs. short exposures. There are also pre-launch flats, and while these will lack the OTA illumination pattern, they may have some benefits. The spectral properties of the target should also be considered, for example, line emission sources observed in broad-band filters might flatten better with the appropriate narrow-band flat. In summary, given the various problems and complications impacting WFPC flat fielding, it is probably true that there is no single correct way to flatten the data; instead it is a matter of choosing the compromises which give an adequate result without undue effort.

VII. Future Plans

We are in the process of obtaining about 1300 new Earth-calibration exposures as part of the Cycle 3 closure calibration. These include observations of most filters alone, and many crossed with both the F122M and F8ND filters. Our goal is to deliver a complete set of new calibration flats for most filters in 1994. We will attempt to remove the neutral density patterns wherever possible, by using both ratios derived from the Earth-cals and from sky flats. The beautiful work on sky flats by the MDS groups provides a powerful tool for deriving and checking removal of the neutral density patterns. We may also attempt to derive sky flats in other filters besides F555W and F785LP, provided there is sufficient data in the archive.

Finally, we emphasize that input from the user community is welcomed and solicited, regarding not only flat fielding, but all aspects of WFPC calibration. The user community, as a group, have unparalleled expertise and resources, and it is our sincere hope these considerable capabilities may be brought to bare on difficult aspects of WFPC calibration.

VIII. Further Information

Additional information regarding the WFPC flat fielding can be found in:

- Image headers for flat field calibration files. These contain descriptions of how the reference files were derived.
- Selected WFPC Instrument Science Reports and Memos, available from STScI Science Instruments Branch.
- Space Telescope Electronic Information Service (STEIS) Memos, which are available by anonymous FTP to internet node stsci.edu. These contain up-to-date information on calibration reference files, etc.
- STSDAS Calibration Guide, available from STScI User Support Branch.

- WFPC Handbook, available from STScI User Support Branch.
- WFPC Final Orbital / Science Verification Report, 1992, ed. S. Faber, available from STScI User Support Branch.
- WFPC Instrument Science Reports and Memos, available from STScI Science Instruments Branch.

References

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