Early Assessment of the WF4 Anomaly

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ABSTRACT
A new anomaly has been discovered in the WF4 channel of WFPC2 which is characterized by sporadic images having low or zero bias levels. Early beginnings of the problem can be traced near the time of Service Mission SM3B in March 2002 where images begin to appear with progressively lower and lower bias levels. By mid-2004 some images appear with very low bias levels – far below the normal 311 DN, and in February 2005 the first images with zero bias level are seen. As of this writing all images are significantly below normal bias levels, and nearly 30% have zero bias level. While the calibration pipeline will correct for low bias levels, close examination of these images reveals faint horizontal streaks (<1 DN RMS) and low photometry (up to 70% low for faint targets at very low bias and gain 15); these effects are correctable and preliminary corrections are given in the Appendices.

Images with zero bias, however, suffer much more serious problems -- these are blank except for brightest pixels and the data are not recoverable. Both A-to-D gains 7 and 15 show similar anomalies, though the onset is slower at gain 15 due to its greater digitization range. Extrapolation of current trends suggests gain 7 will become completely unusable in mid-2006 while gain 15 will produce some useful data until late-2006. Fortunately, the other WFPC2 CCDs appear unaffected by the anomaly, and show no evidence for early onset of similar problems. Examination of bias levels during periods with frequent WFPC2 images shows low and zero bias episodes every 4 to 6 hours. This periodicity is driven by cycling of the WFPC2 Replacement Heater, with the bias anomalies occurring at the temperature peaks. We suggest that lowering the Replacement Heater temperature set points by a few degrees C might effectively eliminate the WF4 anomaly.
Introduction
WFPC2 was installed into HST in December 1993 and has operated remarkably well during its 12 years on orbit. Aside from the shutter anomaly which was repaired, and CTE losses in the CCDs which is a relatively minor issue, there have been no major failures of the instrument. A new and challenging anomaly was recognized in data from the WF4 CCD in late October 2005. Long-term trending of the anomaly suggests we are likely to lose the WF4 CCD during 2006 unless a work around can be found. Herein we examine the long- and short-term evolution of this anomaly, and its impacts on imaging, photometry, and the GO science program. Many of the images currently being obtained with WF4 will suffer some form of corruption – either streaks in the background and/or low photometric counts; preliminary corrections for these issues are given in the Appendices A and B. Finally Appendix C outlines a possible strategy to mitigate the anomaly.

Discovery of the Anomaly
The anomaly was discovered while updating trending plots of the WFPC2 dark current in late October 2005. It was noticed that the dark current for WF4 was anomalously low on 9/21/2005. This dark current was estimated by combining calibrated dark images in sets of five (.c0x files), and then performing statistical analyses on the combined image. Two of the five images used on that date (U948HA02M and U948HA03M) had a background level of zero and showed only cosmic rays and hot pixels, without the usual background dark current (few DN) and noise. Inspection of the raw uncalibrated images (.d0x files) showed these were similar in appearance to the calibrated images, and had a background level of zero instead of the normal level ~311 DN. The bias level determined from the over-scan columns1 was also zero rather than the bias level. This effectively ruled-out any problems with the calibration pipeline and implied a hardware issue with the camera. A plot was made of the bias levels of all WFPC2 images since early 2003 (Figure 2), and it was immediately apparent a serious problem had developed in WF4.

Long-Term Trending of the WFPC2 Bias Levels
From late 1994 until early 2001 the WF4 bias level appeared relatively stable at 311 DN with a standard deviation of ~1 DN. However, beginning in March 2002, roughly at the time of Service Mission SM3B, the lower envelope of the distribution began to fall, and by the end of 2002 there were a few points as low as 305 DN. This is shown in Figure 1 where we have plotted the “biaseven” header parameter (wp2_biaseven_4 in StarView) against date. This trend continues into 2003 with the bias level becoming more and more unstable and reaching lower and lower values (Figure 2). At this point the scatter in the WF4 bias values is clearly

1 The over-scan columns are extra readouts performed after each CCD row has been readout, and as such represent the “zero level” of the detector in the absence of any signal.
larger than that of the other CCDs. During the last half of 2004 the problem becomes more serious with sporadic images falling very far below the normal bias level – some as low as 70 or 80 DN. In February 2005 the first incidences of zero bias occur and subsequently these become more frequent. By late 2005 the upper envelope of the distribution is falling, and there are no longer any images at the old normal bias level (311 DN) – all images are significantly low, and by late Nov. 2005 there are a total of 266 zero bias images.

Figure 1. WF4 CCD bias levels during 2001 and 2002 for A-to-D converter gain 7. Total of 23799 images plotted. Image type BIAS is excluded since bias levels are not available in StarView.
Figure 2. CCD bias levels for WFPC2 images at A–to-D converter gain 7 vs. time. Total of 17,666 images are plotted spanning 1/1/2003 to 10/25/2005. Image type BIAS is excluded since bias levels are not available in StarView.

Similar effects are seen at A-to-D converter gain 15 (Figure 3). Development of the anomaly is essentially the same as gain 7. The first image with zero bias level occurs later at gain 15, in late July 2005 rather than Feb. 2005, but it is likely this merely reflects the greater range of CCD output voltages that can be read at gain 15 vs. gain 7, and not some fundamental difference.

Since both A-to-D gains have similar effects but different electronics boards, we can conclude that the anomaly must be early in the CCD signal processing chain – either on the CCD itself or immediately following the CCD.
Figure 3. Same as Figure 2 but for A-to-D converter gain 15. Total of 3498 images are plotted.

Figure 4 plots the fraction of anomalous images on a monthly basis. Two degrees of degradation are plotted – images with bias <280 DN and images <5 DN. As we will see later, images with bias <280 DN begin to show significant image quality problems (e.g. horizontal streaks and photometry errors >5%) hence this was chosen as a fiducial point where the anomaly first becomes important. Most images in this range are probably recoverable, however. Beginning at the second limit, bias levels <5 DN, images suffer much more serious problems, and are effectively blank and unrecoverable. As we can see, the fraction of images suffering both levels of degradation is growing rapidly. By late 2005 nearly all images have bias levels <280 DN and hence are significantly impacted. By this same date approximately 1 in 3 images have zero bias and are effectively lost.

We can attempt to predict the future of WF4 using Figure 4. Extrapolating the Low + Zero Bias curve, we would estimate that all images will be impacted (bias <280 DN) by Dec. 2005. Noting the similar shape of the two curves, and that fact that the Zero Bias curve reaches a given level about 9 months after the Low + Zero Bias curve, we would estimate that all images will have zero bias around August 2006. From Figure 2 and Figure 3 we can see that the onset of zero bias images is later at gain 15 than gain 7, while Figure 4 plots both gains together. Hence all gain 7 images will have zero bias (and be effectively unusable)
starting somewhat earlier – perhaps July 2006, while all gain 15 images will have zero bias starting about 5 months later or around Dec. 2006. These dates are of course only approximate, and could occur earlier or later depending on how rapidly the zero bias condition evolves.

**Figure 4.** Fraction of anomalous images vs. date. Includes both gain 7 and 15, but not raw BIAS frames as these do not have the bias level available in StarView. Data are plotted through 11/28/2005.
The bias levels for the other CCDs -- PC1, WF2, and WF3 -- have been highly stable the entire time with variations less than about 1 DN. Occasional high points are seen, especially in CCD WF2, but these are believed to be caused by optical effects in the camera, and not any electronic anomaly. At gain 15 high values are seen for PC1 at regular intervals, but these are caused by a known data archive “feature.” We see no evidence for any electronic anomaly in the other CCDs. Given that Figure 2 already shows increased scatter of the WF4 bias level in early 2003 -- two years before development of more serious problems -- it seems likely that we are at least several years away from any similar problems in the other CCDs.

**Short-Term Behavior of the WF4 Bias Levels**

Figure 5 illustrates the behavior of the WF4 bias level for all gain 7 images during July 2005, when a large number of WFPC2 images were taken. Most of the images have bias levels slightly below the historically normal values ~311 DN, with occasional departures to low or zero bias levels. Figure 6 and Figure 7 show additional detail over time periods where the bias level is especially well sampled due to frequent use of WFPC2. It appears the bias variations are not completely random, but show a fairly repetitive pattern consisting of precipitous drops to low values or zero, brief periods at or near zero, then somewhat slower recovery toward near-normal values. This pattern shows some periodic behavior with low-bias episodes occurring approximately every 4 hours, though there is occasionally a 6 hour interval between low-bias episodes. As discussed in Appendix C, this periodicity is driven by cycling of the WFPC2 Replacement Heater.

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2 These images with high bias are internal flats taken in partially rotated filter wheel positions through narrow band filters. Due to the filter wheel design, WF2 is exposed to unfiltered light through the filter wheel “clear” position in these rotated settings, and hence becomes highly saturated in these images which are timed for proper exposure in the other CCDs through the narrow band filters. In these highly saturated images charge bleeds into the over-scan columns where the bias level is determined, thus elevating the bias level.

3 Bi-monthly photometric monitor observations are performed with read-out of a single CCD rather than all four CCDs. In these situations, the bias information is stored in the wp2_biaseven_1 parameter, regardless of which CCD was used for the observation. This parameter is normally used for PC1 and hence the bias levels for the other CCDs occasionally show up in Figure 3 as PC1 bias levels.
Figure 5. WF4 bias levels for all gain 7 images during July 2005.

Figure 6. Enlargement of Figure 5 between July 5th and 10th.
Image Quality During Anomalous Bias Levels

On quick examination, images with low but non-zero bias levels (i.e. in the range from about 5 to 280 DN at gain 7) appear normal. This is because the calibration pipeline automatically subtracts the bias level, hence removing the most obvious impact. Closer examination, however, reveals that these images have faint horizontal streaks (<1 DN RMS) superposed on the background in WF4. Images with the bias level at or near zero (i.e. within the read noise of zero) have more obvious problems as these will be blank, except possibly for bright targets and cosmic rays. We will refer to the former images as “low bias” images and the later ones as “zero bias” images.

Figure 8 shows a “low bias” image where all four CCDs have been mosaicked together. Most of the bright features visible in all four CCDs are cosmic rays and hot pixels, as normally expected for this 700 second exposure. A few faint targets are visible in WF2. While the background in PC1, WF2, and WF3 is nearly flat, the background in WF4 shows obvious bright and dark horizontal stripes and streaks along the CCD rows. Figure 9 shows WF4 in greater detail. The RMS amplitude of the horizontal streaks in this example is 0.61 DN. While large variations in the bias level are seen on timescales of hours (i.e. Figure 7), the bias level appears to be stable to better than about 1 DN during the 13.6 seconds required...
to read out the CCD.

In an effort to get a statistical picture of the streak intensity among different images, we have plotted the RMS streak intensity vs. bias level in Figure 10 for 450 dark images taken during 2004 and 2005. The WF3 data are also plotted and give an indication of what can be expected for normal images – normally the RMS streak intensities are in the range 0.08 to 0.18 DN; presumably this represents small background fluctuations due to noise, cosmic rays, etc. For WF4 we see that images with normal bias levels (>300 DN) tend to have streak intensities within the range expected for normal images. But once the bias level falls below about 280 DN many images have elevated streak intensities. And at bias levels below about 200 DN virtually all images have significant streaks, with the RMS intensities ranging from about 0.3 DN to 1.2 DN. While these results are for gain 7, we expect similar properties at gain 15. The distribution of data points in Figure 10 appears to be identical for the 2004 and 2005 data, with the only difference being that the 2004 data do not yet extend to very low bias levels.

The streaks are easily removed from the “low bias” images, provided the images contain only small targets (i.e. less than ten to twenty pixels in size). Appendix A gives a preliminary iraf script to remove the streaks.

“Zero bias” images, i.e. ones where the bias level has fallen to zero, are nearly blank since most data values fall below the a-to-d converted zero point and hence most of the image is zero (e.g. Figure 11). Sufficiently bright targets and cosmic rays may still be visible, if their data values extend above the a-to-d converter zero point. Calibrated images will contain a faint negative imprint of the calibration images (bias and dark reference files) which have been subtracted from it in the calibration pipeline. While these images will not be useful for most purposes, some exceptions might be astrometry and imaging of bright targets.
Figure 8. Example of a “low bias” science image, U96R0206M, which is a 700s exposure in F439W taken on 12 June 2005 at gain 7. The bias level in WF4 was 49 DN, which is far below the normal value ~311 DN.
Figure 9. Example of "low bias" image; enlargement of WF4 CCD in Figure 8.
Figure 10. Background streak RMS intensity vs. bias level for 450 dark frames at gain 7. The WF4 data for 2004 and 2005 are plotted separately. For comparison the WF3 data for 2005 are also shown. The streak RMS is measured using the iraf script given in Appendix A.
Figure 11. Example of “zero bias” science image U96R2401M showing CCD WF4. This is a 900s exposure in F336W taken on 16 June 2005 at gain 7. The bias level in WF4 was 0 DN. A few bright cosmic rays are visible, as well as a faint negative imprint of the calibration reference files.
Photometry During Anomalous Bias Levels

It is important to consider whether the electronic problem that causes anomalous bias levels might somehow also corrupt the photometry. We have examined data from internal flats as well as photometry with standard stars, and it appears the photometry is indeed corrupted, though in fairly repeatable, and perhaps correctable ways.

Figure 12 shows the observed counts, scaled so the normal count level is 1.0, as a function of the bias level. The data are internal flats (so-called IFLATS or INTFLATS) at gain 7 with various filters and exposure times from the Internal Monitor calibration programs (programs 10067, 10072, 10075, 10356, 10360, and 10751). The upper envelope of points is the 10 second F555W IFLATS; there are 233 points and they normally have about 1000 DN per pixel; these are the brightest images in the plot. Images near the normal bias level ~311 DN have the expected normal count levels, but as the bias level decreases the counts also decrease. The decrease is very smooth and reaches a point near zero bias level where the image has roughly 80% of the normal counts. Once zero bias is reached, the images have even lower count levels (points along the left axis).

Data are also plotted for the 6 second and 8 second IFLATS that are available, and these points generally lay below those from the 10 second data, and have approximately 600 and 800 DN per pixel, respectively. A small number of 1800 second F390N IFLATS were also available and are plotted; these normally have around 70 DN per pixel and lie farther below data from brighter images.

In an effort to get data at very low target count levels, we have measured the 10 second F555W IFLATS in a region of the CCD which falls in the shadow of the pyramid mirror (specifically the region bounded by [6:15,201:600]). This region typically has ~15 DN per pixel, and these data define the lower envelope of points in Figure 12. These reach as low as 60% of the normal count levels as the bias level approaches zero. These “shadow” points tend to have a larger scatter than the other data, both due to the lower count levels, and due to variation in contamination of the CCD window which scatters light into the shadow region.

Results for gain 15 are plotted in Figure 13, and in general the curves are very similar to those for gain 7. The main difference is that the curve for faint count levels is somewhat

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4 Here we use so-called IFLATS or INTFLATS where closed shutter blade is illuminated by a number of lamps surrounding the shutter. Since the A and B shutter blades have different reflectivities, we have treated each blade separately.

5 We have measured the median counts per pixel in the central 400 x 400 pixels of each image, and then divided this number by the average median counts for the twenty images nearest the normal bias level.
lower than that for gain 7. The faint points reach about 30% of the normal count level at gain 15, compared to about 60% for gain 7. This difference is fairly easy to understand in terms of A-to-D conversion of the CCD output – the gain 15 data are merely the extrapolation of the gain 7 data to lower CCD output levels. Gain 15 is able to record CCD output levels a factor ~2 lower than those at gain 7, before hitting the floor (or zero) of the A-to-D conversion. This is why the gain 15 data reach about 30% of the normal counts, compared to about 60% for gain 7, for low bias levels with faint targets.

In addition to the IFLAT data, Figure 13 also includes data for standard star GRW+70D5824. Most of the data are from program 10356 on 6/25/2005, though there are three points from earlier programs and dates. Table 1 gives more detail on these data. For consistency with the IFLAT data which are in units of counts per pixel, we have used the median counts per pixel within the stellar image\(^6\) for Table 1 and when plotting in Figure 13\(^7\). The stellar data in Figure 13 fall well within the envelope defined by the IFLAT data.

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<thead>
<tr>
<th>Table 1. Standard star GRW+70D5824 data for Figure 13.</th>
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<td>(6) We defined the median counts per pixel within the stellar image as the counts within a pixel where the sum of all brighter pixels contains 50% of the light.</td>
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<td>(7) Ideally one would plot each pixel of the PSF separately, for full consistency with the IFLAT results, but PSF variations, random positioning on the pixel grid, etc., make this impractical when comparing low bias and normal counts.</td>
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From Figure 12 and Figure 13 it is apparent that photometry can be significantly impacted by the bias anomaly. Near-normal bias levels will have near-normal photometry. But as the bias level decreases the target counts will decrease by an amount which depends on the target brightness – bright targets at gain 7 can be as much as 20% low for bias levels near zero, while faint targets can be 40% or more below the normal brightness. At gain 15 bright targets can be as much as 25% low for bias levels near zero, while faint targets can be 70% or more below the normal brightness.

This behavior can be easily explained in a model where both the decrease in bias level and decrease in target counts are caused by a reduction in the gain of some amplifier early in the signal chain. For example, if this amplifier were perfectly linear and working with a zero point corresponding to approximately negative 1240 DN, a gain reduction to 80% of normal would also be accompanied by a reduction of bias level from 310 DN to near-zero DN. Additional effects, such as the larger reduction for faint targets, would need to be explained by other details such as non-linearity at low count levels.

Some good news is that the relations in Figure 12 and Figure 13 appear more-or-less time-independent. Even though the data span several years, all the points lie close to their respective curves for a given brightness level. A preliminary set of equations that can be
used to correct the photometry for gain 7 data are given in Appendix B.

New observations are planned in proposal 10772 to better calibrate WF4 photometry in the presence of the bias anomaly. Multiple observations of standard star GRW+70D5824 are planned monthly in both gains 7 and 15. VISFLATS are also planned using rotated ramp filters, which should provide a wide range of brightness levels (near zero to near saturation).

![Photometry vs. Bias Level - Gain 7](image)

**Figure 12.** Photometry as function of bias level at gain 7 for WF4. The vertical scale shows the ratio between measured counts and normal counts for the images; the horizontal scale gives the bias level. Data are from various internal flats with the normal brightness (DN or counts per pixel) given in the legend.
Impacts on Observer Science

In the near-term most images suffer only from the “low bias” version of the anomaly, and these data can probably be recovered. The streaks can be removed from the images, and the photometry can be corrected, though probably with some increased noise and uncertainties. However, the more serious “zero bias” version of the anomaly is rapidly growing more common, and it seems certain that we will soon face a situation where WF4 is completely unusable. Even in this situation, the science impact for many programs will be relatively minor. The default apertures are located on PC1 and WF3; hence programs with pointed observations at small targets should be unaffected. On the other hand, programs with large targets, or survey programs requiring a large field-of-view, will lose approximately one-third of their imaging area. Wide-field imaging in the blue and UV is in fact one area where WFPC2 still possesses some unique capabilities.

In an effort to ameliorate the situation, we are attempting to move WFPC2 Prime observations earlier in the HST schedule, where this is feasible and desirable. We have reviewed all un-executed WFPC2 Prime observations in Cycle 14, and identified those that
would seem to benefit most from this, and will attempt to move those first, followed by the others.

It may also be beneficial in the short term to move some observations to A-to-D gain 15, as this will allow greater bias range before zero bias is reached. However, this would need to be weighed against the poorer noise sampling in the other CCDs at gain 15 vs. the relative importance of WF4.

Some modes that specifically require WF4, for example, some settings of the Linear Ramp Filters, Quad Filters, and Polarizers, will become infeasible with the loss of WF4. However, these modes are little used, and in some cases ACS has similar capabilities (e.g. polarimetry).
Comments on the Nature of the Hardware Problem

Since both A-to-D gains have similar effects but different electronics boards, we can conclude that the anomaly must be early in the CCD signal processing chain – either on the CCD itself or immediately following the CCD.

The strong correlation between the bias level and photometric loss (i.e. Figure 12 and Figure 13) might be most simply explained if both are caused by a gain variation in some amplifier located either on or near the CCD. An amplifier with a zero point below the A-to-D converter zero point could explain both the bias variation and photometric loss as gain variations. The larger photometric loss at gain 15 is also consistent with such a picture, as it would tolerate much lower gain excursions before it’s A-to-D zero point is reached.

Conclusions

We have described a new anomaly in the WF4 CCD of WFPC2 which is characterized by sporadic images with low bias level. The first evidence of low bias occurs around Service Mission 3B (March 2002) when images begin to appear in WF4 with bias levels a few DN below the normal 311 DN. By late 2004 the anomaly has become more severe and many images have bias levels in the range 50 DN - 290 DN, and as of late 2005 all images have bias <290 DN. The calibration pipeline automatically measures and subtracts the bias level from images, so at first glance the calibrated images might appear normal. But more careful examination will show that these “low bias” images typically have weak (1 DN RMS) horizontal streaks, and low photometry -- up to ~40% low at gain 7 for very low bias levels and faint targets (and up to 70% low at gain 15). The streaks and photometry are probably repairable and preliminary corrections are given in the Appendices.

Starting in Feb. 2005 we see the first images reaching zero bias, and these currently represent about 30% of the images taken. These ”zero bias” images are essentially blank, except for very bright pixels. They are not recoverable, and will not be useful for most science purposes. As the anomaly continues to worsen, we expect a point to be reached where all images have zero bias and are thus unusable. This point might be reached in mid to late 2006.

On a positive note, we have noticed a strong correlation between temperature peaks in the WFPC2 electronic bays and episodes of low and zero bias (Appendix C). These temperature peaks occur every 4 to 6 hours as the WFPC2 Replacement Heater cycles on and off. If the electronics bay temperatures could be lowered by a dew degrees C, the WF4 anomaly might greatly reduced or eliminated.
Appendix A: Removal of Streaks from “Low Bias” Images

Below we give an iraf script for removal of the streaks in WF4. The comments in the script describe how to run it, etc., and should be self-explanatory. It uses a combination of median filtering and Gaussian filtering along image rows to produce an image of the streaks, which is then subtracted from the image. The Gaussian filter is designed to remove features larger than about 250 pixels, and hence real targets approaching this size may be adversely affected by the algorithm. Figure 14 and Figure 15 show examples of before and after images.

```
procedure streak4(input)
#
# This script processes images from an input list,
# removes the streaks from WF4, and outputs images
# with the same names into a subdirectory "fixed".
#
# A table listing the image names, their WF4 bias levels,
# and WF4 streak intensities is also output to file "streak_list".
#
# A subdirectory "scratch" is created in the "fixed"
# directory and used for temporary files. These temporary
# files are not deleted after the final image is processed.
#
# The streak intensity is measured with the streaker.cl
# algorithm.
#
# The only script input is the name of the file containing
# the list of the images to be processed.
#
# to run:
#
# Copy both this script and the st.par file to the
# directory where the input images are. Then...
#
# cl
# stsdas
# hst
# too
# imgt
# task streak = "streak4.cl"
# streak junk < image_list
#
# Where "image_list" is a list of input images to
# be processed, one per line. This file can be generated by
# ls *.c0h > image_list
#
# This version works only on 4-group GIES format WFPC2 images.
#
# A copy of the generated streak image is left in the
# scratch directory as "streak.hhh".
#
# JB 24nov2005
#
string input {prompt = "Name of input file?")
begin
string expression, input2, output2, name, text, junk, junk2
string resultsfile, out, scr, files
real fval, upper, lower, fstreak, fbiaseven
# set and creat directories
out="fixed/
scr="fixed/scratch/
!mkdir fixed
!mkdir fixed/scratch
# set name of output text file
!rm fixed/streak_list
resultsfile=out//"streak_list"
# print results to file
files="image           biaseven    streak RMS"
printf (%47s\n",files)
printf (%47s\n",files,
        >> resultsfile)
#
# loop through input file containing image names to process
while(scan(text) != EOF){
    # copy the input image to the scratch directory
    imcop(text//"[1]",scr//text//"[1/4]")
imcop(text//"[2]",scr//text//"[2]")
imcop(text//"[3]",scr//text//"[3]")
imcop(text//"[4]",scr//text//"[4]")
    # delete old scratch files
    imdel(scr//"qq*.hhh")
imdel(scr//"streak.hhh")
    #
    # start processing wf4:
    # exclude edge of image
    input2=text//"[4]"
name=input2/"[3:798,3:798]"

imcop(name, scr//"qq1.hhh")

# compute image median
imstat(scr//"qq1.hhh[100:750,100:750]", fields="midpt", lower=-10, upper=10,
     nclip=3, lsigma=3., usigma=3.,
     binwidth=0.1, format=, mode="ql") | scan (fval)

# set high and low regions to median
upper=fval+4.
lower=fval-4.

expression="if im1 .gt. "/upper/" then "/fval/" else im1"
imcalc(scr//"qq1.hhh", scr//"qqup1.hhh", expression)

expression="if im1 .lt. "/lower/" then "/fval/" else im1"
imcalc(scr//"qq1.hhh", scr//"qqout1.hhh", expression)

# convolved with broad gaussian in X
gauss(scr//"qq1.hhh", scr//"qqgauss1.hhh",100.,ratio=0.001,theta=0.,
     nsigma=3., bilinea+, boundar="reflect")

# iterate #2
expression="if (im1-im2) .gt. 2. then im2 else im1"
files=scr//"qqout1.hhh,"//scr//"qqgauss1.hhh"
imcalc(files, scr//"qqlo2.hhh", expression)

expression="if (im2-im1) .gt. 2. then im2 else im1"
files=scr//"qqlo2.hhh,"//scr//"qqgauss1.hhh"
imcalc(files, scr//"qqout2.hhh", expression)
gauss(scr//"qqout2.hhh", scr//"qqgauss2.hhh",100.,ratio=0.001,theta=0.,
     nsigma=3., bilinea+, boundar="reflect")

# iterate #3
expression="if (im1-im2) .gt. 2. then im2 else im1"
files=scr//"qqout2.hhh,"//scr//"qqgauss2.hhh"
imcalc(files, scr//"qqlo3.hhh", expression)

expression="if (im2-im1) .gt. 2. then im2 else im1"
files=scr//"qqlo3.hhh,"//scr//"qqgauss2.hhh"
imcalc(files, scr//"qqout3.hhh", expression)
gauss(scr//"qqout3.hhh", scr//"qqgauss3.hhh",100.,ratio=0.001,theta=0.,
     nsigma=3., bilinea+, boundar="reflect")

# zero the streak image
imstat(scr//"qqgauss3.hhh[100:750,100:750]", fields="midpt", lower=-10, upper=10,
     nclip=3, lsigma=3., usigma=3.,
     binwidth=0.1, format=, mode="ql") | scan (fval)
imarith(scr//"qqgauss3.hhh","-",fval,scr//"qqgauss3x.hhh")

# generate results:
# repaired image
imarith(scr//"qq1.hhh","-",scr//"qqgauss3x.hhh",scr//"qqxxx.hhh")
imcop(input2,scr//"qqfinal.hhh")
imcop(scr//"qqxxx.hhh[1:796,1:796]",scr//"qqfinal.hhh[3:798,3:798]")
# final output image
imcop(scr//text//"[1]",out//text//"[1/4]")
imcop(scr//text//"[2]",out//text//"[2]")
imcop(scr//text//"[3]",out//text//"[3]")
imcop(scr//"qqfinal.hhh",out//text//"[4]")
# streak image
imcop(input2,scr//"streak.hhh")
imarith(scr//"streak.hhh","*",0.,scr//"streak.hhh")
imcop(scr//"qqgauss3x.hhh[1:796,1:796]",scr//"streak.hhh[3:798,3:798]")
# stats on streak image
imstat(scr//"streak.hhh[50:750,50:750]",fields="stddev",lower=indef,upper=indef,
     nclip=0,lsigma=3.,usigma=3.,
     binwidt=0.1,format=-,mode="ql") | scan (fval)
fstreak=fval
# get BIASEVEN value
hedit (input2,"BIASEVEN",".") | scan (junk,junk2,fbiaseven)
# print results to file
printf ("%20s %10.3f %10.3f\n",input2,fbiaseven,fstreak)
printf ("%20s %10.3f %10.3f\n",input2,fbiaseven,fstreak,
     >> resultsfile)
}
end
Figure 14. Example of WF4 “low bias” image: science image U96R0206M before streak removal. Pixel values from -3 to +5 DN are displayed. WF4 bias level was 49 DN.
Figure 15. Same image as Figure 14 after application of the streak4.cl procedure.
Appendix B: Correction of “Low Bias” Photometry

Herein we outline a preliminary photometric correction for WF4 data. We envision that the correction consists of two parts – a linearity correction and a gain correction. The former is an additive correction applied to the raw level (either bias level or bias + target counts) in each pixel, and corrects for non-linearity in either the amplifier and/or the A-to-D converter which might occur at low signal levels. The later is a multiplicative correction applied to the target counts (per pixel), and might represent gain errors due to the failing amplifier. Both corrections are functions of the bias level only. These corrections would be applied to each pixel of the affected image.

The linearity correction is applied as

\[ x' = x - f(x) \]

where \( x \) is the raw signal from the A-to-D converter, and can be the bias level or the bias plus target counts, \( x' \) is the corrected counts, and \( f(x) \) is some function. For a calibrated image, the correction would hence be

\[ c' = c - f(c+b) + f(b) \]

where \( c \) is the calibrated target counts, \( b \) is the bias level, and \( c' \) is the corrected calibrated counts.

Here we use a third-order polynomial for \( f(x) \) below some fixed value of \( x \), and zero or no correction above that value. Through trial-and-error we found this function works well and effectively eliminates the dependence on target brightness:

\[ f(x) = 0 \text{ for } x \geq 290 \text{ DN} \]
\[ = 4[(290 - x)/290] + 30[(290 - x)/290]^2 + 20[(290 - x)/290]^3 \text{ for } x < 290 \text{ DN} \]

The linearity correction is illustrated by Figure 16. Applying this correction to Figure 12 produces the modified plot in Figure 17 where all points now lie along the same curve independent of target brightness.

The second correction, the gain correction, is applied as a multiplicative correction to the target counts as a function of the bias level

\[ c'' = c' / g(b) \]
where $c''$ is the final corrected target counts, $c'$ is the linearity corrected counts, and $b$ is the bias level$^8$. A fourth-order polynomial was used for $g(b)$ and fit to Figure 17 with the result

$$g(b) = 1.0 \quad \text{for } b \geq 290 \text{ DN}$$

$$= 0.848 - 1.96e-4 \ b + 5.96e-6 \ b^2 - 3.20e-8 \ b^3 + 6.45e-11 \ b^4 \quad \text{for } b < 290 \text{ DN}.$$  

The final result with both linearity and gain corrections applied is shown in Figure 18. All data points are now within a few percent of the expected values. Additional data are needed to validate this correction over wider sets of bias levels and target counts. Similar corrections should be possible for gain 15, but this is left for future work.

Figure 16. Linearity correction as function of raw image counts.

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$^8$ Here $b$ is the bias level from the data header without correction for linearity issues.
Figure 17. Revised Figure 12 after application of linearity correction. The horizontal axis is the bias level without linearity correction.
Figure 18. Revised Figure 12 after application of both linearity and gain corrections. The horizontal axis is the bias level without linearity correction.
Appendix C: Correlation of Bias Levels and Bay Temperatures, and a Possible Mitigation Strategy

As suggested by ARB team, we have correlated the bias levels with various temperatures reported in the WFPC2 data headers. A remarkable correlation is found between the bias anomalies and the Bay 1, 3, and 4 temperatures (Figure 19). Apparently the low bias episodes occur during peaks in the Bay temperatures. For example, the WF4 bias level plummets whenever the Bay 1 temperature rises about 12.5 degrees C.

These temperature swings are in fact driven by the WFPC2 Replacement Heaters whose “on” and “off” states are also indicated in the Figure (i.e. RPLHTR). These heaters are located in Bay 1, Bay 3, Bay 4, and also in the Camera Head Electronics. The heaters are regulated by comparing the Bay 1 temperature against lower and upper set points which are set in software. The heaters switch “on” when Bay 1 reaches a lower temperature set point of 11 degrees C, and switch “off” when an upper set point of 15 degrees C is reached. In this way, the heaters and temperatures cycle with a period of several hours.

Figure 19. Representative plot of WF4 bias level on 17 to 19 July 2005 with WFPC2 Bay 1, 3, and 4 temperatures superposed. There is an obvious correlation between temperature peaks and low-bias events. The temperatures are regulated by the Replacement Heater (RPLHTR) whose “on” and “off” cycles are indicated by red circles (ON = marks at 50 units. / OFF = marks at 0 units).
As seen in Figure 20 the correlation between WF4 bias level and Bay 1 temperature evolves strongly over time. In July 2004 the maximum temperature near 15 degrees C only lowers the bias level from ~311 DN to ~280 DN. But a year later the same temperature swing will send the bias level to zero. Apparently the bias levels are becoming increasingly sensitive to temperature variations, due to some on-going failure in the electronics. We have also studied the long-term temperature trends, and there is no obvious long-term variation.

![Bias Level vs. Bay 1 Temp](image)

Figure 20. Correlation between WF4 bias levels and Bay 1 temperatures at three different epochs.

This Figure also suggests a possible way to mitigate the anomaly. It appears that the bias level is always near-normal when the Bay 1 temperature is near the lower limit of 11 degrees C. Hence it appears that a slight lowering of the temperature might eliminate most of the anomaly. For example, re-adjusting the Replacement Heater set points to say 10 and 11 degrees C, might eliminate essentially all of the low-bias episodes, at least in the near-term. Moreover, there would seem to be little chance of unexpected adverse effects, since this temperature is only slightly outside the present operating range.

Eventually the failure that is at the heart of the anomaly may continue to progress, and someday the anomaly might again reappear. But that time might be far in the future, and one could consider further lowering of the temperatures at that time.