UVIS Flat Fields Affected by Shutter-Induced Vibration

H. Kurtz, P. R. McCullough, S. Baggett

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ABSTRACT

Image ratios of short internal tungsten flat fields exhibit faint diagonal striping along a direction coincident with the shutter edge travel. We investigate the phenomenon using additional archival data, both internal and external, and develop a model to quantify the amount of variation observed across the field of view. We find 1) no evidence for striping in external images, 2) the stripes are limited to short (<10s) internal exposures and 3) the stripes’ amplitude is noticeably higher in images taken with the B shutter blade. Specifically, blade A image striping is typically 0.1% or less peak to peak while the blade B striping is typically 0.5% or higher peak to peak for 1 s exposures. We interpret the lack of striping in external images as an indication that the effect is not directly related to the low-level blurring of the PSF observed in short (<10s) external exposures that has been attributed to shutter-induced vibrations of the WFC3 pick-off mirror or the M1 mirror. Instead, we interpret the striping effect as a shutter-induced vibration of an optical element in the internal light path of the calibration subsystem.

1 Introduction

The Wide Field Camera 3 (WFC3) UVIS channel has a duplicate of the ACS WFC shutter design. This is a disk consisting of two closed and two open sections referred to as shutter A and B (Figure 1). The shutter (rotating disk) sits between the filter wheel and the CCD housing and is mechanically and electronically capable of rotating both clockwise and counter clockwise. However, the flight software rotates the shutter in only one direction.
The effect is the blade sweeps across the field of view from the corner of amplifier D in the lower right up to the corner of amplifier A in the upper left (Sahu et al. 2015).

![Figure 1: Sketch of the WFC3 UVIS shutter. The ‘beam foot-print’ is indicated (figure from Baggett, 2003).](image)

We assess the possible contribution of the shutter behavior on the UVIS photometric results. For example, in ISR 2017-15, aperture photometry of staring mode observations of white dwarf standards (GD153 and GRW70) as a function of time and wavelength show 2-3 times the expected scatter over short timescales (Figs 8-10). In ISR 2017-21, photometry of spatial scans of white dwarf standards – scanning mode provides significantly higher signal-to-noise than staring mode. Most observations show excellent results yet some data show 2-3 times the expected scatter. That is, neither staring nor scanning mode routinely achieve the expected short-term photometric scatter, i.e. results within the nominal error budget (based on propagated errors from Poisson statistics and calibration files). This discrepancy raises the question of whether the shutter behavior may be introducing some uncertainty into the photometric results.

2 Data

For our investigation we use archival data consisting of a large number of short internal tungsten flat fields. These images are an ideal dataset to assess the shutter performance, as they provide fine time sampling (every 0.5 - 3 days). We supplement this data with other, less frequently acquired data such as deuterium flats, Earth flats, and external images, to
see if the corrugation of internal flat field ratios is related to the shutter vibrations (chatter) or e.g. lamp vibrations (stroboscopic) effect.

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Table 1: Proposals for the data used in our analysis.

2.1 Tungsten Flats

The tungsten flats originate from a bowtie monitoring program used to prevent hysteresis on the UVIS detector. This is accomplished via frequent short, 3-image visits. The first image is a 1 second flat to detect if any hysteresis is present. The second image is a 200 second flat that intentionally saturates the detector in order to neutralize any hysteresis. The final image is a 1 second flat used to verify that the hysteresis has been removed. All of these images are taken in 3x3 binned mode. A three image visit was taken every 3 days in 2017 (more frequently in the past), for a total of 3,984 images spanning June 2009 - October 2017. We examine the 1-second images as ratios both to one another (i.e., for each visit, image 3 compared to image 1) and to representative reference images from 2012 (i.e. image 1 from a visit compared back to a 2012 image 1, image 3 from a visit compared back to a 2012 image 3). The ratios normally serve as a test for whether the hysteresis, if present, has been neutralized but for our study, we use the ratios to assess the shutter performance. These images have a signal to noise of $\sim 10,000$ -e.

2.2 Deuterium Flats

The deuterium flats are chosen from the UVIS Internal Flats calibration proposals used to monitor the stability of the UV filters and to check the flat field structure. We select only flats with short exposure times (3.4s) because the shutter effect is attenuated in longer exposures. This yields 23 deuterium flats (filter F200LP) from the proposals listed in Table 1. These flats have an average of 22,000 -e/pixel.

2.3 Earth Flats

Earth flats as the name implies, are observations of the Earth, chosen from the UVIS Earth Flats program. The original intent of the Earth Flats was to check the filters and to validate the L-flat solution. Here we employ the short exposure time (less than 5s) Earth
flats as an external check of the shutter behavior. We examine a total of 140 Earth flats in filters F656N, F469N, F336W, F343N, F373N, F395N, F390M. Of the 140 flats, 98 have high signal to noise (greater than $\sim 10,000$ \(-e\)) and half of those were observed using shutter B. Table 2 is a summary of the Earth flats examined, giving their exposure time and the number of observations at that exposure time.

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Table 2: Earth flat data used in our analysis.

2.4 Jupiter Images

For a second external illumination source, an extended target with good signal to noise in a short exposure time, we chose Jupiter. These Jupiter images are not ideal as they are sub-arrays, however, other targets (e.g. other planets) did not sufficiently fill the field of view or were too faint (e.g. sky flats). The Jupiter observations are taken from the Jovian Transit of Venus program. We examine the data taken with filter F763M as those images have exposure times of 0.48s. In total we examine 63 images of Jupiter.

2.5 Mars Images

An additional external source we examine is Mars. The Mars images were taken on a sub-array of a small section of the detector. These images were taken from proposals 14499 and 15456 in 2016 and 2018 respectively. We use data taken in filters F673N and F410M with an exposure time of 0.48s. In total we examine 11 images.

2.6 Moon Images

We also examined images of the Moon from proposal 12537. Of the 20 images only 3 were able to be examined due to lost guide stars and variations in the observed field. The 3 images each have an exposure time of 0.48s and are observed with filter F502N. We had to align these images to one another before we could ratio them. The images had to be translated and rotated to align. Because of slight misalignments and changes of the trailed PSF, lunar features did not divide well, so we were therefore unable to see if corrugations were present.
3 Analysis

3.1 Tungsten Flats

We analyze tungsten flat image ratios from the bowtie monitoring program. Figure 2 shows a typical tungsten flat, illustrating the lamp illumination pattern (brighter in lower right and dimmer in the upper left), the chip gap, dust specks, and a few bad pixels. Figure 3 shows the ratio of two tungsten flats with contours. The illumination pattern ratios out but we are left with diagonal stripes, which align along the direction of the shutter blade motion. We look at ratios of flats taken with shutter A to those with shutter B as well as ratios of shutter A to A and shutter B to B. Of the images compared to a shutter B image 65% of them show the visible corrugation at a level of $\sim \leq 0.02\%$.

A model of the shutter edge motion across the field of view, with the rotation axis of the shutter as in Figure 1, reproduces the geometry of the striping in the tungsten flat ratios (Figure 4). Figure 4 shows the motion of the shutter across the detector and the division of what we are calling sectors that mark that motion.

Figure 5 shows the median within the sectors, as a function of sector number, for B to B and A to A tungsten ratios. As the figure illustrates, shutter B typically exhibits a $\sim 0.4\%$ higher variation than shutter A; based on a visual inspection of a 50 of these plots there is no apparent time dependence to the variations.

Anomalous behavior in shutter B was noticed in ground test data (Hartig 2008). In that case a 12 mas blur was noted in the PSF data attributed to possible ($< 1$ arcsecond RMS) vibrations in the pick off mirror or the M1 mirror (Hartig 2008). This effect was confirmed in early on-orbit data: the PSF FWHM is systematically larger (by $\sim 20\%$) in images taken with shutter B than A for exposure times less than about 1s (Sabbi 2009). Longer exposure time images are less affected. The blur in short images seems to appear constant on-orbit (Sahu et al.2015).
Figure 2: A typical full frame internal 3X3 binned tungsten flat field. The grey scale is +/- 10%, where white is high signal. Amps A and B are at the upper left and upper right corners respectively; amps C and D are at the lower left and lower right respectively. The same image orientation is used consistently throughout the ISR unless noted otherwise.
Figure 3: A typical tungsten bowtie ratio with over-plotted contours. The grey scale is +/- 2.5%, where white is high signal.
Figure 4: Map of the shutter sectors. The model motion of the shutter across the detector is based on a 3x3 binned images from bowtie observations. Each sector is approximately 1.6 arcsec. The color shows the model motion as a gradient.
3.2 Deuterium Flats

WFC3 has two lamps in the calibration system, tungsten and deuterium, for visible and UV flats respectively. Given the corrugation seen in the tungsten image ratios, we inspected image ratios taken with the deuterium calibration lamp to see if the corrugations are present there as well. Figure 6 shows a typical deuterium flat. These flats have more features than the tungsten flats. Here we see the crosshatch pattern (from the manufacturing process) and the dark spot in lower left, which is attributed to something on the housing of the deuterium lamp (Rajan et al., 2010). Figure 7 is a typical ratio of two deuterium flats along side a ratio of two deuterium flats which show the corrugation. Even with the features unique to the deuterium lamp, a clear signature of the corrugation is visible. Three of 23 (13%) of deuterium ratios show evidence of corrugation at a level we could discern (∼0.2%).
Figure 6: Typical full frame deuterium flat field. The gray scale is +/- 5%, where white is high signal. Amps A and B are at the upper left and right corners respectively; amps C and D are at the lower left and right respectively.
Figure 7: The left is a typical deuterium flat ratio and the right is the ratio of iaan08o1qflt.fits and iaan05hbqflt.fits with the contours over-plotted. Corrugations typically are not evident (left) but sometimes are (right) in deuterium flat ratios. The gray scale is +/- 1.5%, where white is high signal.

3.3 Earth Flats

Given that images with both types of calibration lamps exhibit the corrugations, we investigated external images. If the corrugation is due to a common element present in both internal and external light paths, we would expect at least 5-10% of short external exposures to show the corrugations, based on their longer exposure time, their S/N and because of small number statistics.

We start with Earth flats; a typical one is shown in Figure 8. Earth flats can have parallel streaks in the image from the scene of Earth moving across the detector. Figure 9 shows the ratio of two Earth flats; this ratio is relatively featureless except for some of the streaks. Although in a similar direction as the tungsten and deuterium corrugations these streaks in the ratio are not the same effect, because the streaks are parallel to the direction of the spacecraft motion (green arrow). Also the streaks are all parallel to each other, whereas the shutter effect is as in Figure 4 nearly vertical at lower right to nearly horizontal at upper left.

About 50% of the Earth flat images we examine have streaks. We form the image ratios using a relatively streak-free image in the denominator. Inspection of the image ratios shows many with streaks in a direction inconsistent with the internal corrugation pattern. For the ratios with streaks in the direction of the corrugation we over plot on the image ratios
parallel lines along the direction of the spacecraft’s motion. In this manner we rule out any Earth flats as having corrugations like the internal flat ratios, implicating a calibration system component as the cause of the corrugations.

Figure 8: Typical full frame Earth flat image. The gray scale is +/- 5%, where white is high signal. The streaks are the scene below along the direction of motion of the spacecraft.
3.4 Jupiter Images

We use Jupiter images as a second type of external illumination source to confirm the Earth flat findings. The Jupiter images are more difficult to ratio than the internal flats as there are rotational and positional shifts of Jupiter between the images. Furthermore, the Jupiter observations are not full frame but sub-array. Figure 10 shows a Jupiter image and Figure 11 shows a typical ratio of two Jupiter images. For Jupiter we would expect to see 2-3 corrugations across the angular diameter of the planet, but we see no evidence for corrugations. This lack of corrugations is consistent with the Earth flat results.
Figure 10: Typical sub-array Jupiter image. The gray scale is +/- 30%, where white is high signal.
Figure 11: Typical Jupiter sub-array ratio. The gray scale is +/- 20%, where white is high signal.

3.5 Mars Images

We use Mars images as an additional external illumination source similar to Jupiter. The Mars images produce better ratios than the Jupiter images, as the rotation of Mars is not as extreme. On the other hand, the angular diameter of Mars at opposition in these cases is only 23 arcseconds, so we would expect only 1 period of a typical sinusoidal corrugation across the angular diameter of the planet. Again we see no evidence for corrugations.
Figure 12: Typical sub-array Mars image. The gray scale is +/- 15%, where white is high signal.

Figure 13: Typical Mars sub-array ratio. The gray scale is +/- 20%, where white is high signal.
4 Discussion

An important conclusion of the previous analysis is that the corrugations in the ratios of two short exposure flat fields are seen with internal illumination and not seen with external illuminated exposures. If the cause were shutter chatter (i.e. non-uniform rotational velocity of the shutter blade) resulting in non-uniform effective exposure time at various positions across the detector, then we would expect it to occur for both internal and external illumination. Thus, we conclude the cause of this effect is not shutter chatter.

In addition to that empirical, observational evidence, here we make a physical, theoretical argument that the shutter cannot chatter quickly enough to explain the corrugations. Based upon Figures 4 and 3, the corrugations have a characteristic period of $\sim 10$ sectors, or $\sim 2.5$ degrees of shutter rotation. The shutter’s nominal rotational velocity is $V = 180$ degrees s$^{-1}$, and its minimum lead-in angle is $\sim 20$ degrees (Rossetti 2008). The latter 20 degrees is the angle the shutter must rotate from its nominal closed position to the point at which the first corner of the CCD is illuminated. Hence, we model its acceleration as $A = 9$ degrees s$^{-1}$ per degree, so that it can achieve 180 degrees s$^{-1}$ in 20 degrees starting from rest. Ideally, from when the leading edge of the shutter reaches the beam footprint to when the trailing edge leaves the beam footprint, the shutter’s angular velocity is constant. However, what if that isn’t the case: i.e. if the shutter chatters? As a working example, let us suppose that at some point in its nominal rotation, the shutter chatters: it decelerates, accelerates, and then decelerates again to its nominal rotational velocity (Figure 14). In this illustrative scenario, the velocity changes from $V$ to a minimum at position B, returns to $V$ at position C, reaches a maximum at position D, and decreases to $V$ again at position E. At most points on the detector, the variations in shutter velocity average out because the beam footprint is not near an edge of the shutter when the accelerations are occurring. However, for those pixels corresponding to the beam footprint being near an edge of the shutter when the accelerations are occurring, the effective exposure time will be different than nominal. From point A to point B, the shutter rotates 0.6 degrees in our example, as it does from point B to C, and from C to D, and from D to E; thus, from point A to point E, it rotates 2.4 degrees, i.e. approximately the observed (angular) period of the corrugations. At the nominal angular velocity $V = 180$ degrees s$^{-1}$, that 2.4 degrees corresponds to $\sim 13$ milliseconds or $\sim 75$ Hz. From A to B, the 0.6 degrees of travel takes 0.003384 s compared to 0.003333 s for a nominal velocity of 180 degrees s$^{-1}$, i.e. it takes 51 microseconds extra time. From A to C, it takes 102 microseconds extra. From A to D, it’s back to 51 microseconds, and from A to E, the accelerations and decelerations have canceled out, so there’s no extra time compared to a constant velocity sweep of the shutter. However, for pixels illuminated for a nominal time of 1 second, such as the bowtie monitor exposures, a maximum extra exposure time of 102 microseconds would correspond to a brightening of 1E-4, or 0.01%. For comparison, the typical corrugation amplitude is $\sim 20$ times larger, i.e. $\sim 0.2\%$ for ratios of 1-s bowtie images taken with shutter B. We conclude that to explain the observed corrugations with chatter, the shutter would need to experience angular accelerations $\sim 20$ times larger than it does in its ramp-up or ramp-down in nominal operation.
We propose the corrugations as a stroboscopic effect – that the internal illumination source is varying temporally in brightness or its optical coupling to the detector is varying temporally. It would be easy to imagine that the incandescent lamp’s filament is vibrating in and out of the focal point of the lens that shines it toward the CCD. However, we also see corrugations with the deuterium lamp, which is a more diffuse, vapor source. In the end, we do not have a convincing hypothesis for which optical element explains the stroboscopic effect.

However, like we did with chatter, we can estimate the potential for a stroboscopic effect to explain the observed corrugations. Let’s imagine that as the shutter blade rotates 1.2 degrees, i.e. half of a corrugation period, the lamp is effectively OFF. It does not actually need to turn off, but perhaps its light no longer couples well to the CCD. In that case, the pixels corresponding to a shutter edge passing over them during that OFF period would experience $1.2/180 = 0.0067 \text{ s}$ less exposure of the nominal illumination. For the 1-s bowtie exposures, that’s 0.67%, which is $\sim 3$ times larger than the 0.2% amplitude of corrugations that we observe in bowtie ratios. We conclude that there’s adequate potential in a stroboscopic effect to explain the observations.

We note that the accelerometer measurements taken at GSFC with the instrument in a vertical configuration to simulate the zero-g environment of an orbit, the instrument (measured at B-latch, C-latch, and the pick off mirror) vibrates with a lowest-frequency spike in the power spectrum at $\sim 100 \text{ Hz}$ (Rossetti 2008, Figure 20). The same measurements also show that shutter B induces greater vibration than shutter A, consistent with our analysis.
of the image ratio corrugations being much larger for shutter B than shutter A.

Finally, we examined data provided by S. Casertano of visit 46 of program 13335 (Figure 15). In those WFC3 UVIS images of stars obtained with HST scanning at \( \sim 7.5 \) arcsec s\(^{-1}\), or \( \sim 190 \) pixels s\(^{-1}\), the vibration induced when the shutter is rotated open or closed is evident in the cross-trail motion of stars for \( \sim 0.5 \) s at the beginning and end of star trails, corresponding to the start and end of each exposure. These oscillations too occur at \( \sim 70 \) Hz. The vibration is apparent from \( Y=300 \) to 430 (130 pixels, or 0.7 s) and from \( Y=830 \) to 870 (40 pixels or 0.2 s).

Figure 15: An example of the examined shutter B data provided by S. Casertano of visit 46 of program 13335. The black points are the cross-trail sums (summing from - 8 pixels to +8 pixels wide) and the red points are the black points with a 5 pixel boxcar smoothing applied.

5 Conclusions

The light corrugations seen in internal (tungsten and deuterium) flat fields are not present in external images such as Earth flats, Jupiter, or Mars images. Therefore we conclude that the corrugation is due to the vibration of part of the calibration system (e.g. a stroboscopic effect) that is not part of the external source path. Possible points of vibration are the calibration lamps or the calibration optics. The corrugation thus appears to be due to a different phenomenon than the slight blurring seen in PSFs (Sabbi, E. 2009 & Sahu et al.2015) in very short external images. We confirm that shutter B vibrates more than
shutter A as found in previous analyses (e.g. Sahu et al. 2015) resulting in corrugation that is about 5 times larger in B than A.

**Acknowledgements**

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