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Dithering strategies for WFC3

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ABSTRACT

In this report we describe different dithering strategies for WFC3. This includes moving the telescope by steps large enough to step over detector artifacts and the use of sub-integer pixel steps to recover some of the spatial information lost due to the under-sampling of the point spread function by both WFC3 detectors. For both the UVIS and IR channels, we describe the different detector characteristics that have to be taken into account in order to derive an optimal dithering strategy. A number of dither patterns for different scenarios are presented.

Introduction

Dithering is a technique where an observation is divided into multiple exposures that are spatially offset by moving the telescope by a small shift compared to the detector size. This places the target on different locations on the detector, which helps to increase the quality of the combined image. Moving the detector an artifact-specific distance makes it possible to remove defects or non-optimal pixels. These could be individual hot or dead pixels, bad rows or columns, other defects. Also, effects of pixel-to-pixel errors in the flat-field or pixel-to-pixel sensitivity over the detector are reduced. For detectors with a chip gap, dithering can be used to fill the gap in order to produce a complete image. Using sub-integer dithers helps improve the spatial sampling of the point-spread function (PSF), which is particularly important for HST since the PSF is under-sampled in most of the instruments.

Using large offsets comparable to the size of the detector to increase the field-of-view is normally referred to as mosaicking. The main focus of this report is dithering, but we also comment on mosaicking. More information on dithering can be found in the Multidrizzle Handbook (www.stsci.edu/hst/HST_overview/documents/multidrizzle) and the Instrument Handbooks of the individual HST instruments (www.stsci.edu/hst/HST_overview/instruments). For details on the reconstruction of under-sampled images using dithering, see Lauer (1999).

This ISR is organized as follows. First we give a general overview of dithering and its benefits. We thereafter described the UVIS and IR channels on the WFC3 detector and go through the different detector characteristics that have to be considered in order to plan a dithering strategy. Next we describe the set of pre-defined dither patterns available in the Astronomers Proposal Tool (APT). We thereafter give recommendations for specific dithering strategies to be used with UVIS and IR, respectively. Finally, we give examples on how to construct patterns in the APT before ending with a Summary.

General dithering strategies

Why dither?

As mentioned in the Introduction, there are four main reasons for dithering:

- Remove bad pixels and other detector artifacts
- Improve the sampling of the point-spread function
- Improve photometry by averaging over flat-field errors
- Fill the gap between detector chips, here specifically WFC3/UVIS

Furthermore, the effects of cosmic ray hits are mitigated when using multiple exposures, as is the case with dithering.

When to dither?

In general, it is always recommended to use dithers in order to get the best possible scientific return of WFC3 exposures. There are only a very few special cases where dithering may not be optimal. This includes observations of time-variable sources where high accuracy on relative photometry is desired. Moving the object between transient bad pixels and pixels with varying flat-field response and errors may not be optimal in these cases. Also, if there are significant intra-pixel sensitivity variations, then moving the object may compromise measurements of differential changes of photometry with time. This was a concern for NICMOS, but was not found to be an issue for WFC3 (WFC3 ISR 2008-29). Finally, for short exposures less than a few minutes, the relative increase in time spent on overheads may be significant, and in some cases lowering the signal-to-noise to a level that compromises the advantages with dithering.

How many dithers?

Using many dither positions helps to recover the PSF, avoid detector artifacts and exclude areas hit by cosmic rays. At the same time, dividing the available observing time into multiple exposures decreases the achievable signal-to-noise. The decreased signal-to-noise is due to both the extra spacecraft overheads needed to perform the dithering and an increase in read noise due to the multiple exposures. The extra data volume will also fill the data buffer faster, possibly requiring additional buffer dumps that affect the available science exposure time. The number of dithers is therefore a trade-off between these goals. The rule of thumb is to use as many dithers as possible while maintaining the required signal-to-noise. If resampling the PSF is essential, then four dither points are required, while in cases where the spatial sampling is less important and high accuracy photometry is the goal, then two or three dither positions could be sufficient.

The number of dithers needed to exclude cosmic rays depends on the exposure time. A minimum of two is needed for short exposures (<1000s), although three is recommended. For long exposures, (>1800s), up to 4-5 dithers are needed to minimize the effect of cosmic rays. Having multiple exposures to exclude cosmic rays is essential for UVIS observations. For the IR channel, cosmic ray rejection can generally be done effectively in the image processing due to the up-the-ramp sampling used in IR detectors, if the ramp includes enough samples for a good fit to the count rate.

For more information on overheads and orbit time determination, see Chapter 10 of the WFC3 Instrument Handbook. The APT is also helpful for determining how long and how many exposures can be fitted within an orbit. One important note is that UVIS observations less than 350s require serial buffer dumps, which effectively shortens the time available for science exposures during an orbit. For exposures of 350s or longer, the buffer dump can be made in parallel resulting in more time available for observation. Therefore, if observations with planned exposure times below 350s can be extended to 350s or above without causing problems with saturation, then this is preferred since more science observing time can be extracted from the orbit.

Using sub-pixel steps to improve spatial resolution

Using two or three step sub-pixel dithers helps to improve the spatial sampling, while a "full" recovery of the PSF is possible with a 4-point dither pattern. It is possible to construct 6-point and 8-point patterns if extremely accurate PSF sampling is desired, but in general a 4-point pattern recovers most of the spatial information. Below we list sub-pixel steps to be used in addition to integer steps for optimal PSF resampling:

- 2-point pattern: (0, 0), (1/2, 1/2)
- 3-point pattern: (0, 0), (1/3, 1/3), (2/3, 2/3)
- 4-point pattern: (0, 0), (0, 1/2), (1/2, 0), (1/2, 1/2)
- 6-point pattern, cross the 3-point dither with a 2-point (1/2, 0) dither: (0, 0), (1/3, 1/3), (2/3, 2/3), (1/2, 0), (5/6, 1/3), (1/6, 2/3)
- 8-point pattern, cross the 4-point dither with a 2-point (1/4,1/4) dither: (0, 0), (0, 1/2), (1/2, 0), (1/2, 1/2), (1/4, 1/4), (1/4, 3/4), (3/4, 1/4), (3/4, 3/4)

Note that if the 6-point or 8-point patterns have to be divided into two contiguous orbits, then the HST pointing stability will affect how well the patterns can be executed. With an rms precision of 0.005 to 0.020 arcsec in the pointing for contiguous orbits, the orbit-to-orbit rms shift in pixels is ~0.13-0.5 pixels for UVIS and ~0.04-0.15 pixels for the IR channel. Therefore, executing the 6-point or 8-point patterns over two orbits will be problematic, in particular for the UVIS channel. For more information on the number of dither positions to use and details on the patterns, see section 2.5 in the Multidrizzle Handbook.

Which dither patterns to use?

The dither pattern best suited for a particular program depends on the science goals and the spatial extent of the target. Targets covering only a fraction of the detector may use a different dithering strategy than the case when it is important to have a uniform quality over the whole detector. We discuss different strategies for the UVIS and the IR channels on WFC3 separately below.

Combining dithered images

Dithered images can be combined using software such as Multidrizzle, which is publicly available through STScI (http://stsdas.stsci.edu/multidrizzle/). Starting in January 2010, Multidrizzle is run on images retrieved via the OTFR pipeline, producing a final combined and geometrically distortion corrected image from the individual dithers. Note that the improvement of the geometric distortion reference files that support Multidrizzle is an on-going process.

WFC3 Detectors - overview

The details of the dithering strategies to apply depend on the instrument used. To facilitate the planning for WFC3 observations, we here give a brief introduction to the instrument, focusing on aspects relevant when planning dithering.
WFC3 has two independent channels, the UVIS channel, sensitive at ultraviolet to optical wavelengths (200-1000 nm), and the IR channel sensitive at near-infrared wavelengths (800 to 1700 nm). The channel-selection mirror directs the on-axis light to the IR channel. If the mirror is removed by the CSM (channel select mechanism) the light is directed straight to the UVIS channel. Therefore, only one of the channels can be used at a time.

UVIS channel

The UVIS detector consists of two 4kx2k CCDs with pixel scale 0.04 arcsec/pixel and a field of view 162x162 arcsec. There is a gap between the two chips of about 31 pixels (1.2 arcsec). The PSF has a FWHM of about 1.7 to 2.2 pixels depending on wavelength (see Table 6.7 in the WFC3 Instrument Handbook). Since a well-sampled PSF requires a FWHM of at least ~2.2 pixels, UVIS observations benefit from sub-pixel dithering to improve the spatial sampling.

IR channel

The IR detector consists of a 1kx1k HgCdTe array with pixel scale ~0.13 arcsec/pixel and a field-of-view 136x123 arcsec. The FWHM of the PSF in the IR channel is between 1.0

and 1.2 pixels depending on wavelength (see Table 7.5 in the WFC3 Instruments Handbook). The under-sampling is therefore a factor ~two and sub-pixel dithering is needed to recover spatial sampling.

WFC3 Detectors – peculiarities

Both WFC3 detectors have peculiarities that have to be taken into account in order to get the highest possible science return from observations. Choosing a proper dither strategy can mitigate most of the effects of the artifacts described below.

UVIS channel

Bad pixels

The UVIS bad pixel map flags about 21000 pixels as "Bad detector pixel" (DQ=4) which is only ~0.1% of the total number of pixels. These bad pixels are located in 18 bad columns as shown in Figure 1. The maximum thickness of a bad column is two pixels, therefore a dither pattern that steps at least two pixels in x-direction will recover pixels falling the bad column. In addition, two rows on either side of the chip gap are flagged as "Bad or uncertain flat value" and should also be excluded. Dithering over these rows is necessary when the aim is to achieve a complete image over the whole detector, in which case dithering over the chip gap is also needed.

Chip gap

The gap between the two UVIS detector chips is approximately 1.2 arcsec on the sky, or 31 pixels. Adding the two flagged rows on each side of the chip gap (Figure 1) makes it necessary to use a dither step of more than 35 pixels to bridge the chip gap. The custom dither pattern (described below) uses a fairly conservative approach and uses steps of ~60 pixels to move over the gap.

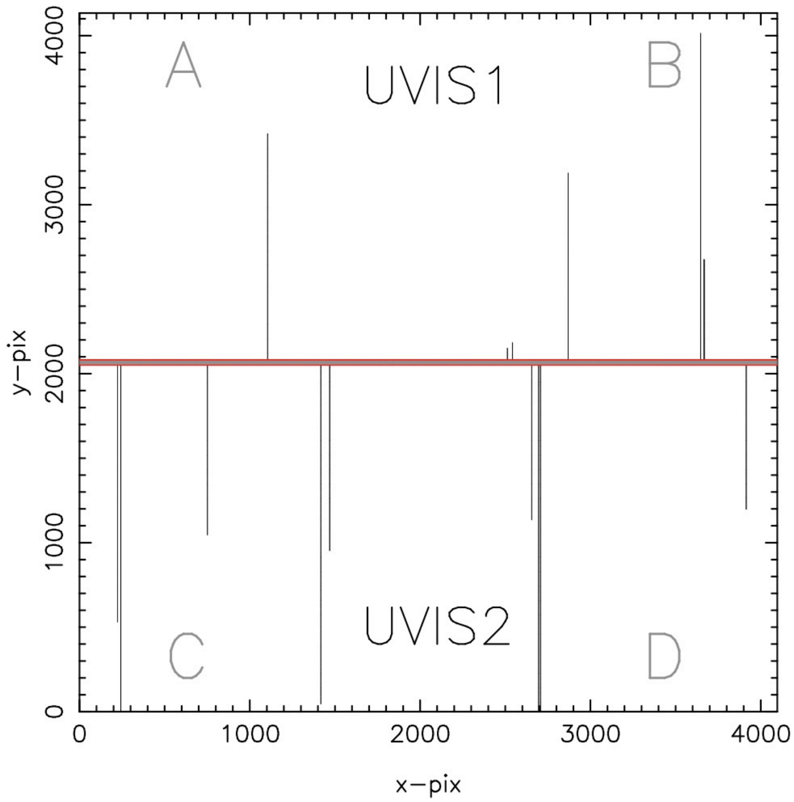

Figure 1. Bad pixels in the UVIS channel. Vertical lines show bad columns, while the horizontal line shows the chip gap, including the two bad rows on either side of the gap.

<u>Droplets</u>

Droplets are artifacts on the outer window of the UVIS flight detector due to mineral residue of a condensation event that occurred during the on ground testing. Detailed information can be found in WFC3 ISR 2008-10. In total, there are approximately 500 droplets, affecting an area of 9%, 24%, 20%, and 33% of the quadrants A, B, C, and D, respectively. The effect of these artifacts is an increased scatter in point-source photometry. Tests have shown that the impact is not significant for large apertures (10 pixel radius). However, for small apertures (3 pixel radius) the photometric scatter increases from 0.5% to 1%. Dithering by 40 pixels should be sufficient for most photometric programs. However, for programs requiring small aperture photometry with less than 1% error in photometry, a step size of at least 100 pixels is recommended to step over the full spatial extent of the droplet features. Note, however, that droplets are not flagged and affected pixels will therefore be included in the median process when combining images. To minimize the effects of droplets, three dithers should be used. Also, for targets with limited size, a recommended strategy is to put the target in quadrant A since this is the least affected by these artifacts.

Cosmic rays

Pixels affected by cosmic rays on CCDs have to be excluded during image combination. This can be achieved either by dividing the exposure using CR-splits or by dithering. Due to the additional benefits using dithering, this is the method recommended. For a 1800s exposure in a SAA free orbit, about 5%-9% of the UVIS pixels are affected by cosmic rays. Therefore, for this exposure time, 4-5 exposures are needed to assure that the number of pixels affected in all images of a stack is negligible (~100 pixels). For shorter exposures, a smaller fraction of the area is affected. It is recommended to use more than two dithers when the exposure time exceeds 1000s.

IR channel

Bad pixels

About 16000 pixels are currently flagged as "bad" pixels in the IR data quality array with data quality flags DQ=4 (dead pixel), DQ=8 (bad zeroth read value), or DQ=32 (unstable). In total, this affects ~1% of the IR pixels. However, recent studies show that correct pixel values can be recovered by the pipeline for pixels with DQ=8. Not counting the 5000 pixels with DQ=8, there remains 11000 bad pixels. The spatial distribution of the flagged pixels, here including DQ=8, is shown in Figure 2 as black areas (gray dots are "IR blobs" described below). The large circular area at pixel ~[358, 54] is the "Death Star" which is commented on in the next subsection. There are also high concentrations of affected pixels in most corners of the detector as well as along the top central part. In any normal case, there is no reason to try to recover the affected pixels around the edges of the chip. Only when mosaicking is it important to take these into account and apply a sufficient overlap so that the effect of bad pixels can be mitigated. Not counting the bad pixels in the death star and around the edges, there are approximately 12000 bad pixels distributed over the detector area (8400 after excluding DQ=8). Most of these are isolated single pixels, but there are also areas with multiple contiguous bad pixels. A small integer pixel dither step is for most cases sufficient to step over most of the bad pixels. Using a single step of at least two pixels recovers ~98% of the pixels that are flagged as bad. A three-step dither pattern with a step size of at least two pixels recovers more than 99% of the bad pixels. These numbers are somewhat approximate since they don't take into account the non-linear geometric distortion. But the rules of thumb should be to use steps of at least two pixels and to use at least three dither positions in order to recover as high fraction of the bad pixels as possible.

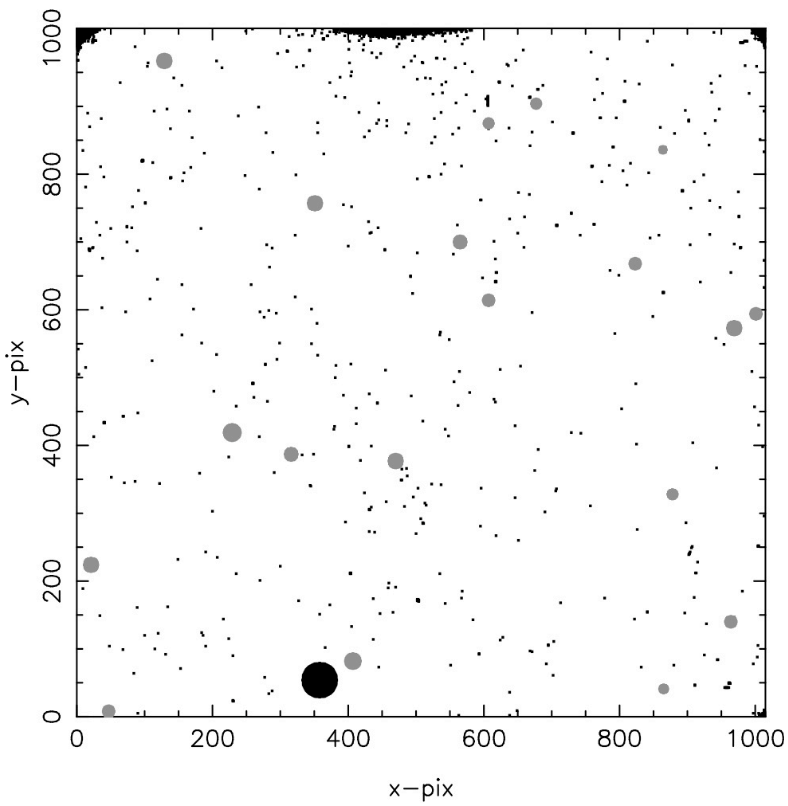

Figure 2. Bad pixels in the IR channel are shown as black dots. The large black feature at the bottom is the Death Star. Gray circles mark areas affected by IR blobs (see text).

<u>Death Star</u>

The large circular area of pixels centered at (358,54) with poor response to light is referred to as the Death Star (e.g., WFC3 ISR 2009-23). The diameter of this feature is 51 pixels, corresponding to over 6 arcsec. (See Figure 2.) It is possible to dither over the death star by using steps exceeding 50 pixels. However, note that such large step creates wide areas along the edges of the detector with lower than nominal exposure time due to the dithering. The area with full exposure time will decrease by at least 10% if dithering over the death star. The recommended strategy is to avoid putting targets in the area of the death star, which makes the use of the large dither steps unnecessary. For mosaics it is possible to dither over the death star without loosing the same relative amount of field-of-view, since the larger “detector-size” steps can be constructed to ensure that the edge areas overlap sufficiently to recover the full exposure time.

<u>IR Blobs</u>

IR blobs are small regions where the sensitivity of the detector is lowered by as much as 10-15%. (See Figure 2.) The blobs are caused by artifacts on the CSM mirror (and do therefore not affect the UVIS channel). To date (June, 2010), there are 19 identified blobs, each affecting pixels within a radius of about 10-15 pixels. In total, these features affect ~1.2% of the IR pixels. A detailed description of the IR blobs can be found in WFC3 ISR 2010-06.

It is not yet known if the IR blobs are completely stable (to a few percent) and to what extent a high quality sky flat-field, constructed from actual IR images, might allow a user to correct for the effect of the blobs. As of this writing (June 2010), high signal-to-noise sky flat fields are not available for the IR channel. The current IR flat fields, obtained from the ground and prior to launch, do not include the IR blobs so the photometry of an object that falls on a blob will be affected. To perform as accurate photometry as possible, it is therefore recommended to use dithers to step over the IR blobs and to mask out the affected areas when combining images. To facilitate this, the WFC3 IR bad pixel mask has a unique data quality value 512 assigned to pixels affected by the blobs. The largest diameter of a masked blob region is 25 pixels; therefore, to properly dither over affected areas a dither pattern including at least 25 pixel wide steps should be applied. If the planned target only covers a fraction of the detector, then it should be possible to put the target in an area that is unaffected by IR blobs, thus avoiding the need for the large dithers. A list of IR Blobs is given in WFC3 ISR 2010-06. An up-to-date list can be obtained by examining the most recent IR bad pixel table (or the DQI array of data processed with it) at
http://www.stsci.edu/hst/observatory/cdbs/SIfileInfo/WFC3/reftablequeryindex.

The WFC3 team is currently constructing a small set of sky flat-fields. Due to the nature of sky flat-fields however, it will only be possible to create sky flat-fields for the most used broad band filters (e.g. F160W and F125W). Tests to show to what extent the effect of the blobs can be properly corrected using a limited number of sky flat-fields will be performed as soon as these are available and the results will be presented in an upcoming ISR. Check the WFC3 webpage for updates. For now, the suggested strategy is to avoid using the pixels affected IR blobs by applying sufficient dither steps.

Cosmic Rays

Due to the up-the-ramp sampling of the IR channel, CR hits can generally be effectively filtered out during image processing, if the ramp includes enough samples for a good fit to the count rate. Dithering is therefore not essential for excluding these events in the IR channel. (It is, however, important for moving bad pixels and resampling the PSF.)

WFC3 Detectors – geometric distortion

Images from both the UVIS and IR channels on WFC3 are affected by significant geometric distortion. More detailed descriptions and illustrations of how this affects the detectors can be found in Appendix B of the WFC3 Instrument Handbook. Here we give just a brief summary. The UVIS detectors focal surface in tilted ~21° about one of the diagonals. This produces a rhomboidal elongation of the pixels, and therefore field-of-view, of about 7%. The IR detector is tilted ~24° about the x-axis, causing a rectangular elongation of ~10%. Calculating corrections for these distortions is straightforward. However, the situation is complicated by additional non-linear distortions that affect the plate scale for both detectors. The X and Y plate scales vary only slightly along one diagonal of the UVIS detector, but both scales vary by ~3.5% along the other diagonal, resulting in a variation of ~7% in pixel area on the sky along that diagonal. On the IR detector, the X and Y plate scales vary by ~2.5% and ~6%, respectively, from top to bottom, resulting in a variation of over 8% in pixel area on the sky. The WFC3 team has calculated geometrical distortion solutions to account for these effects (WFC3 ISR 2009-33; WFC3 ISR 2009-34). The coefficients for this solution are included in the IDCTAB reference files for the two detectors and are used by Multidrizzle to produce distortion corrected images.

Even though the distortion can be corrected for in the final images, there are still complications affecting the dithering strategies. Offsetting the target by a fixed distance in arcsec corresponds to moves of a different number of pixels at different locations on the detector because of the variations in plate scale. For large steps, this results in substantially different sampling of the PSF at different locations. For example, if you dither by [25.5, 25.5] pixels in [x,y] at the center of the IR detector, the shifts near the top and bottom edges will be ~[25.2, 24.7] and ~[25.8, 26.3] pixels, respectively. If you dither by [40.5, 40.5] pixels in [x,y] near the center of the UVIS detector, the shift near the corners with the most extreme plate scale variations will be ~[39.8, 39.8] and ~[41.2, 41.2] pixels. *Therefore, it is not possible to use only steps consisting of fractional pixels added to a large integer to effectively resample the PSF over an extended area of the detector. Instead, patterns with large dither steps have to be combined with sub-patterns of small PSF sampling steps if it is important to get good sampling over the full detector area.*

WFC3 Dither Patterns

A number of pre-defined patterns are available in the APT to support dithered and mosaicked WFC3 observations. For both the UVIS and the IR channels, this includes three small-step dither patterns, with two, three, or four dither steps, respectively. In addition there are patterns to facilitate mosaicking and to step over the UVIS chip gap.

Each pattern comes with a default step size (given below), but users can modify the step size, and for certain patterns also change the number of dither steps in the APT to make customized patterns. This also includes the possibility of adding a secondary pattern to some of the primary patterns. For example, if the primary pattern consists of large dither steps, then a secondary pattern with small non-integer steps may be required to resample the PSF if spatial resolution is important for the intended science.

The largest extent of a pattern is approximately 130 arcsec, which is the diameter within which the telescope can be pointed using the same guide stars. Due to the uncertainty in pointing repeatability when switching guide stars, the dithering will be significantly less accurate in these cases.

It is also possible to use POSTARG offsets to move the telescope between exposures when planning observations in the APT. However, using pre-defined patterns to move the telescope creates association files that are used by Multidrizzle in the pipeline processing to make final combined and distortion corrected images. The use of POSTARG offsets does not produce association files and therefore combined images will not be created by the pipeline. Consequently, we recommend the use of patterns instead of POSTARGs when possible.

A summary of the available pre-defined patterns for both the UVIS and IR channels are given below.

UVIS channel

Six pre-defined dither and mosaic patterns are available in the APT for WFC3/UVIS images. The patterns and the default values of the parameters are described here.

- WFC3-UVIS-DITHER-LINE dithers the UVIS aperture by (2.5, 2.5) pixels to sample the point-spread function with fractional pixel steps. The default values are optimized for a 2-step pattern.
- WFC3-UVIS-DITHER-LINE-3PT dithers the UVIS aperture by (2.33, 2.33) pixels to sample the point-spread function with fractional pixel steps. The default values are optimized for a 3-step pattern.
- WFC3-UVIS-DITHER-BOX samples the point-spread function with fractional pixel steps and produces spacings of more than one column to move hot columns. The pixel steps are (0, 0), (4.0, 1.5), (2.5, 4.0), and (-1.5, 2.5).
- WFC3-UVIS-MOS-DITH-LINE has a primary pattern that dithers over the chip gap with steps of: (-4.5, -60.25), (0,0) and (4.5, 60.25) pixels. A secondary pattern adds a dither of (2.5, 1.5) pixels to each of the primary steps.
- WFC3-UVIS-MOS-BOX-LRG produces a UVIS mosaic that can be executed with a single set of guide stars. It dithers the gap between the chips so that no region lies in the gap more than once. The pixel steps are approximately (-1000, -997), (1000, -1001), (1000, 997), and (-1000,1001).
- WFC3-UVIS-MOSAIC-LINE is designed for observations using the full WFC3/UVIS detector for primary exposures and the full ACS/WFC detector for parallel exposures. It dithers over the inter-chip gap on both detectors. The relative steps on the WFC3/UVIS detector are (0, 0) and (36.5, 71.5) pixels.

IR Channel

Four pre-defined dither patterns and mosaic patterns are installed in the APT for WFC3/IR. The patterns and the default values of the parameters are described here.

- WFC3-IR-DITHER-LINE takes steps large enough for photometric accuracy and samples the point-spread function with fractional pixel steps. The relative pixel step between dithers is (3.5, 3.5). The default values are optimized for a 2-step pattern.
- WFC3-IR-DITHER-LINE-3PT takes steps large enough for photometric accuracy and samples the point-spread function with fractional pixel steps. The relative pixel step between dithers is (3.33, 3.33). The default values are optimized for a 3-step pattern.
- WFC3-IR-DITHER-BOX-MIN takes steps just large enough for photometric accuracy and samples the point-spread function with fractional pixel steps. The relative steps in pixels are (0, 0), (4.0, 1.5), (2.5, 4.0), and (-1.5, 2.5).
- WFC3-IR-DITHER-BOX-UVIS is a four-point box pattern that produces an IR mosaic covering the same area as the UVIS detector. The IR imaging is intended to be accompanied by a UVIS exposure (or small dither pattern) using the aperture UVIS-CENTER.

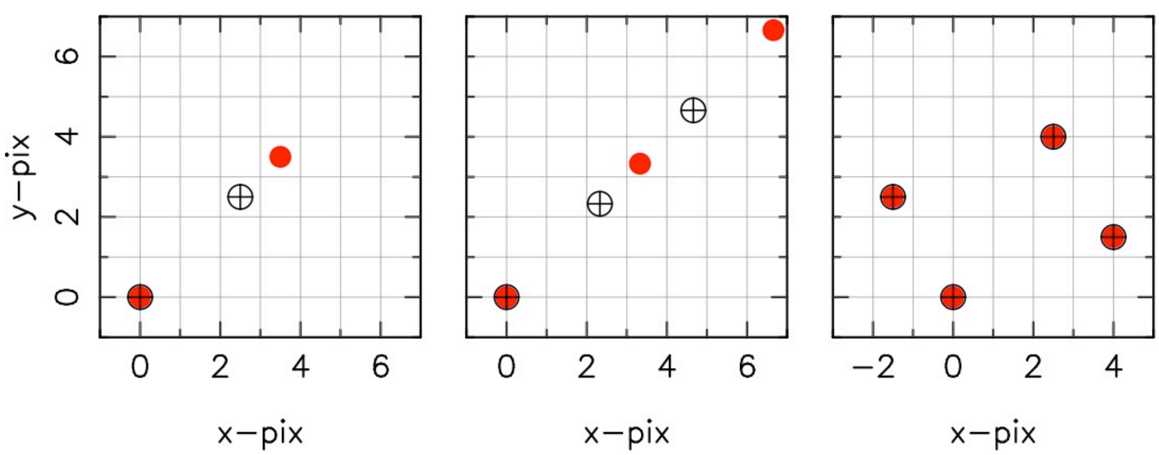

Figure 3. Standard small step dither patterns for the UVIS channel (crossed circles) and the IR channel (filled dots). Left panel shows the "DITHER-LINE" pattern, while the mid panel shows the "DITHER-LINE-3PT" pattern and the right panel shows the "DITHER BOX (-MIN)" pattern.

Figure 3 shows the dither positions for the three pre-defined patterns with small offsets for both the UVIS and the IR channel. These patterns are customized to optimally sample the PSF. The four-point box pattern is preferred, but if signal-to-noise constraints prevent the available observation time to be divided into four exposures (or more), the three or two point dither pattern can be used instead. The additional patterns in the list are special-purpose mosaic patterns, as described above. To date, there are no pre-defined patterns optimized to avoid the effects of detector artifacts such as the blobs and the Death Star in the IR channel and the droplets in the UVIS channel. Below we discuss how to create dither patterns in the case where it is important to avoid these features.

The offsets listed above are most accurate at the central part of the detector and for small steps. Due to geometric distortion in both detectors, the offsets vary over the detector so that the extent of the sub-pixel sampling also changes with location.

More details on the available dither patterns are given in Appendix C in the WFC3 Instrument Handbook.

Specific dithering strategies – UVIS

Using the information and discussions above we are now ready to make more specific suggestions for creating optimum dither patterns for WFC3. As emphasized above, the best pattern to adopt depends on the science goals of the program. The decision-tree in Figure 4 is an attempt to help decide which patterns to use in different situations. Answer the questions in the tree until a set of recommended patterns is reached. The names of the patterns are A2-A8, B2-B8, and C2-C8, where the letters indicate different strategies, while the numbers give the number of dither positions. All the patterns are explained below.

1) First question is if small aperture (3 pixel radius) point-source photometric accuracy with errors less than 1% is required. In this case it is necessary to use 100 pix dither steps to mitigate the effects of droplets. If sampling of the PSF is also required, then at least a 4-point dither pattern is needed, if not, a 2-point pattern could be used at a minimum, even though a 3-point pattern is recommended since this more effectively excludes affected pixels in the median image combination. If the size of the target is limited to a fraction of the detector size, it should preferentially be placed in quadrant A, which has the fewest droplets.
2) If the small aperture point-source accuracy in point 1) above is not essential, the next question is if PSF resampling is important over the whole detector area. In this case at least 4 points are needed if the chip gap is to be filled, while 2 points is the minimum if the gap is not to be filled.
3) Next alternative is if recovering the PSF is important only over a limited area, e.g., if the target covers a small fraction of the detector. In this case a subarray can be used and there should be no need for filling the chip gap.
4) If it is not important to resample the PSF, the remaining question is if the chip gap should be filled. If that is the case, at least one of the dither steps has to be large enough to cover the gap, otherwise a set of small steps should be sufficient.

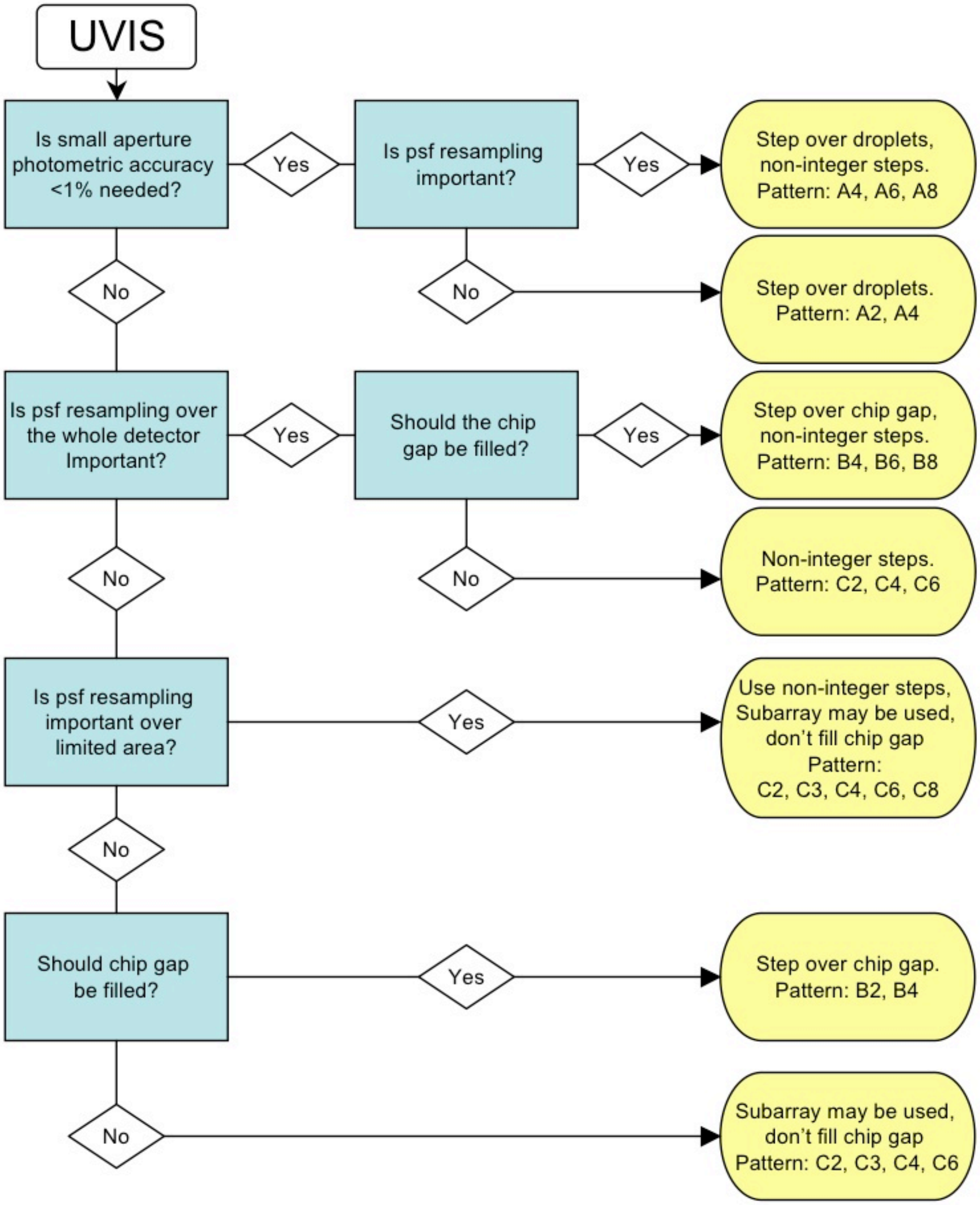

Figure 4. Decision tree for planning dither strategies for the UVIS channel. See text for details.

Recommended patterns

Below we list the patterns given in Figure 4. For each science objective, there are multiple patterns recommended in the figure. In general, choose the pattern with the most possible dithering steps, while keeping the minimum required signal-to-noise needed to achieve the science goals of the program. The impact of cosmic rays should also be considered. A 2-point pattern should preferentially only be used with short (<1000s) exposure times, while at least a 4-point pattern should be used with long (>1800s) exposures (for observations extending multiple orbits).

Dither patterns are here presented in **pixel coordinates**. When constructing patterns in the APT, the dither positions are instead given by a combination of distances in arcsec and orientations in degrees. Examples on how to convert the pixel offsets to quantities that can be used in the APT are given in a later section, where we also give the relation between pixel offsets and POSTARGs. Also, see Appendix C in the WFC3 Instrument Handbook for more information on the relation between the systems.

A-patterns
The A-patterns are constructed to step over the droplets (~100 pixels) for the special case when small aperture point-source photometry with errors less than ~1% is required. A diagonal step is used to limit the effects of geometric distortion. This large step also fills the chip gap. Note that when using a single large step, i.e., a 2-point dither pattern, the pixels affected by droplets will be medianed with a similar number of "good" pixels. To assure that the affected pixels are excluded in the median process, two large steps are recommended. If the spatial extent of the target is limited, then it should preferably be put in quadrant A since this is less affected by droplets. Small sub-pixel steps are used to reconstruct PSF. The large steps are done diagonally to minimize the effects of geometric distortion.

- A2: A single large step over the droplets. Pre-defined pattern WFC3-UVIS-DITHER-LINE can be used if modified.
- A3: Two large steps over the droplets. Pre-defined pattern WFC3-UVIS-DITHER-LINE-3PT can be used if modified.
- A4: A single large step over droplets with additional small sub-pixel steps to sample the PSF. Pre-defined pattern WFC3-UVIS-MOS-DITH-LINE can be used if modified (or WFC3-UVIS-DITHER-BOX).
- A6: Two large steps over droplets, each with additional small sub-pixel steps to sample the PSF. Pre-defined pattern WFC3-UVIS-MOS-DITH-LINE can be used if modified.
- A8: A single large step over droplets, at each position a small 4-point sub-pixel dither box for full resampling of the PSF. Pre-defined pattern WFC3-UVIS-DITHER-BOX can be used as is for each of the two sub-pixel dither boxes. Use POSTARGs for the large move over droplets with equivalent pixel offsets (74.2,74.7).

Table 1. Specifications of the A-patterns

	A2	A3	A4	A6	A8
Step 1	(0.0,0.0)	(0.0,0.0)	(0.0,0.0)	(-74.2,-74.7)	(0.0,0.0)
Step 2	(74.5,74.5)	(74.33,74.33)	(2.5,1.5)	(-71.7,-73.2)	(4.0,1.5)
Step 3		(148.66,148.66)	(74.2,74.7)	(0.0,0.0)	(2.5,4.0)
Step 4			(76.7,76.2)	(2.5,1.5)	(-1.5,2.5)
Step 5				(74.2,74.7)	(74.2,74.7)
Step 6				(76.7,76.2)	(78.2,76,2)
Step 7					(76.7,78.7)
Step 8					(72.7,77.2)

B-patterns

The B-patterns are constructed to step over the chip gap. The large steps are done diagonally to minimize the effects of geometric distortion. Sub-pixel steps sample the PSF.

- B2: A single large step over the chip gap. Pre-defined pattern WFC3-UVIS-DITHER-LINE can be used if modified.
- B3: Two large steps over the chip gap. Pre-defined pattern WFC3-UVIS-DITHER-LINE-3PT can be used if modified.
- B4: A single large step over chip gap with additional small sub-pixel steps to sample the PSF. Pre-defined pattern WFC3-UVIS-MOS-DITH-LINE can be used if modified (or WFC3-UVIS-DITHER-BOX).
- B6: Two large steps over chip gap, each with additional small sub-pixel steps to sample the PSF. Pre-defined pattern WFC3-UVIS-MOS-DITH-LINE can be used if modified. The pattern can also be used as defined in the APT. In this case large steps of ~60 pixels in the y-direction combined with small steps in the x-direction are made.
- B8: A single large step over chip gap, at each position a small 4-point sub-pixel dither box for full resampling of the PSF. Pre-defined pattern WFC3-UVIS-DITHER-BOX can be used as is for each of the two sub-pixel dither boxes. Use POSTARGs for the large move over chip gap with equivalent pixel offsets (45.2,45.7).

Table 2. Specifications of the B-patterns

	B2	B3	B4	B6	B8
Step 1	(0.0,0.0)	(0.0,0.0)	(0.0,0.0)	(-45.2,-45.7)	(0.0,0.0)
Step 2	(45.5,45.5)	(45.33,45.33)	(2.5,1.5)	(-42.7,-44.2)	(4.0,1.5)
Step 3		(90.66,90.66)	(45.2,45.7)	(0.0,0.0)	(2.5,4.0)
Step 4			(47.7,47.2)	(2.5,1.5)	(-1.5,2.5)
Step 5				(45.2,45.7)	(45.2,45.7)
Step 6				(47.7,47.2)	(49.2,47,2)
Step 7					(47.7,49.7)
Step 8					(43.7,48.2)

C-patterns

The C-patterns include small step dithers and do not fill the chip gap. Sub-pixel steps are constructed for an optimal PSF reconstruction.

- C2: A single small step. Pre-defined pattern WFC3-UVIS-DITHER-LINE can be used as is.
- C3: Two small steps in a line offset by (0.33, 0.33). Pre-defined pattern WFC3-UVIS-DITHER-LINE-3PT can be used as is.
- C4: Small dither steps in a 4-point box pattern. Pre-defined pattern WFC3-UVIS-DITHER-BOX can be used as is.
- C6: Similar to C3, but with an additional ½ pixel steps in x-direction at each position. Pre-defined pattern WFC3-UVIS-MOS-DITH-LINE can be used if modified.
- C8: Two small 4-point box patterns are offset by ¼ sub-pixel steps for optimum 8-point PSF resampling. Pre-defined pattern WFC3-UVIS-DITHER-BOX can be used as is for each of the two sub-pixel dither boxes. Use POSTARGs with offsets equivalent to (2.75, 2.75) pixels for the sub-pixel shift between the box patterns.

Table 3. Specifications of the C-patterns

	C2	C3	C4	C6	C8
Step 1	(0.0,0.0)	(0.0,0.0)	(0.0,0.0)	(0.0,0.0)	(0.0,0.0)
Step 2	(2.5,2.5)	(2.33,2.33)	(4.0,1.5)	(2.5,1.0)	(4.0,1.5)
Step 3		(4.66,4.66)	(2.5,4.0)	(2.33,2.33)	(2.5,4.0)
Step 4			(-1.5,2.5)	(4.83,3.33)	(-1.5,2.5)
Step 5				(4.66,4.66)	(2.75,2.75)
Step 6				(7.16,5.66)	(6.75,4.25)
Step 7					(5.25,6.75)
Step 8					(1.25,5.25)

Specific dithering strategies – IR

Following the same reasoning as for the UVIS channel, we now move on to make specific suggestions for the IR channel. The decision tree in Figure 5 is intended to guide the choices.

1) The first question is if a large dither step should be used to step over the Death Star. The general suggestion is to try not to place targets at the Death Star to make the large dither unnecessary. However, there are cases when a dither is required, e.g., if the aim is to create a contiguous mosaic. When stepping over the Death Star, at least a 4-point dither is needed to recover some of information lost due to the under-sampling. A 2-point dither could be used if PSF recovery is not important.

2) If stepping over the Death Star is not required, the next question is if it is important to recover the PSF over the full detector area. At least a 4-point pattern is required to both step over the IR blobs (to get high accuracy photometry) and to get some sub-pixel resampling. If the IR blobs are not stepped over, making photometry less accurate, a 2-point pattern is the least required to recover some of the information lost due to the under-sampling.
3) If PSF sampling is required for a target that covers only a fraction of the detector, then it may be possible to place the target at a detector position that is not affected by IR blobs, making the large dither step unnecessary. Clearly, this will work only if new blobs don't appear on the selected area. A number of patterns with small dither steps can be used; which to choose is a trade-off between required signal-to-noise and how important it is to sample the PSF.
4) Finally, if PSF resampling is not a concern, then the strategy depends of the size of the target on the detector. If the target is small, then the target should be placed at a location on the detector not currently affected by IR blobs and hence dither patterns with only small steps can be used (if new blobs do not appear). For a large target, the IR blobs have to be dithered over.

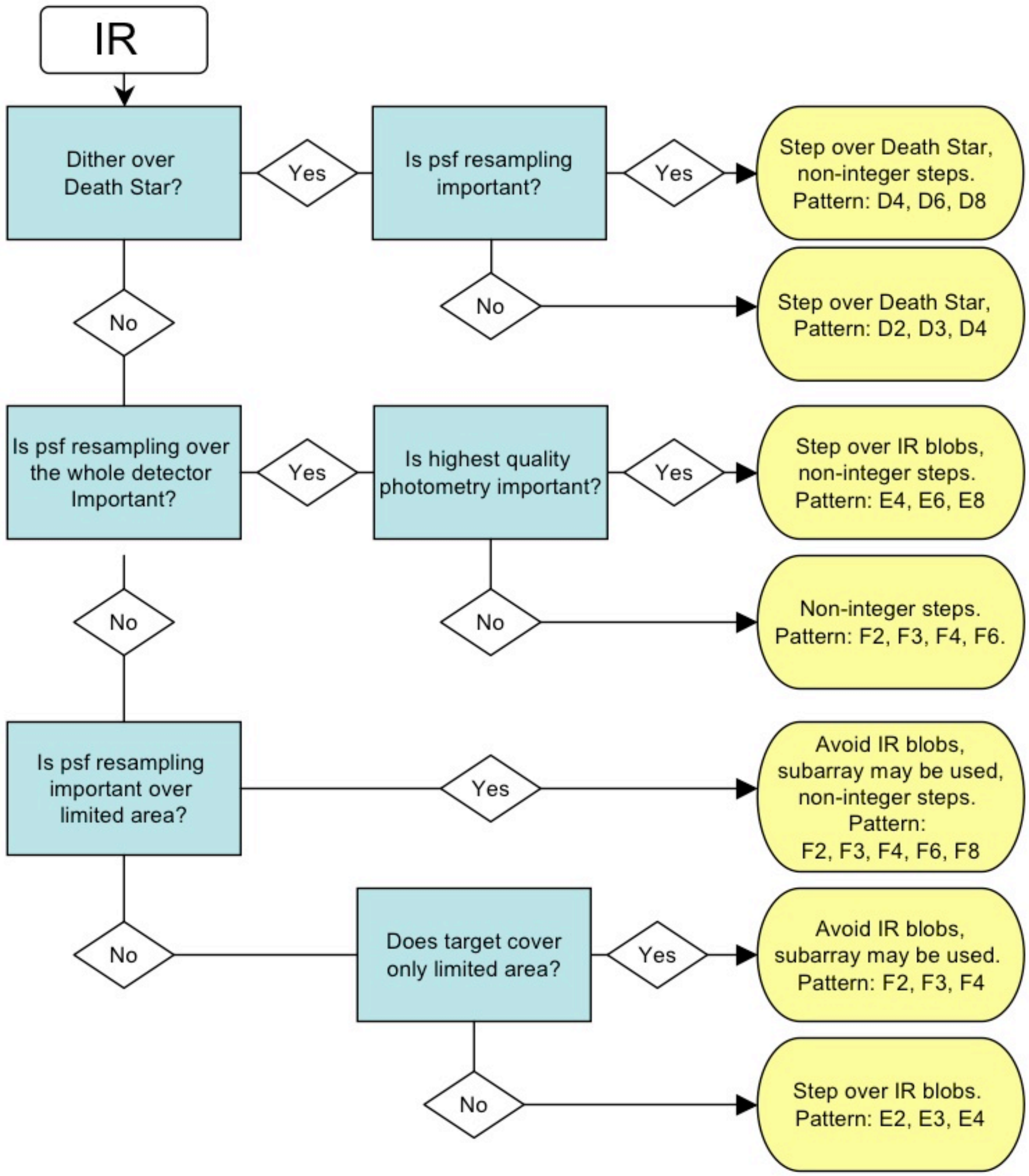

Figure 5. Decision tree for planning dither strategies for the IR channel. See text for details.

Recommended patterns

Below we list the patterns given in Figure 5. For information on how to convert offsets in pixel coordinates to quantities that can be used as input to the APT, see next Section.

D-patterns

These patterns are constructed to move over the Death Star by using a large ~70 pixel step. This also steps over the ~25 pixel wide IR blobs. To avoid the IR blob close to the Death Star (see Figure 2), the shift is done diagonally towards the upper left. Additional small sub-pixel steps are constructed to recover the PSF.

- D2: A single large step over the Death Star. Pre-defined pattern WFC3-IR-DITHER-LINE can be used if modified.
- D3: Two large steps over the Death Star. Pre-defined pattern WFC3-IR-DITHER-LINE-3PT can be used if modified.
- D4: A single large step over Death Star with an additional small sub-pixel step at each position to sample the PSF. Pre-defined pattern WFC3-IR-DITHER-BOX-MIN can be used if modified.
- D6: Two large steps over Death Star, each with additional small sub-pixel steps to sample the PSF. No existing pattern.
- D8: A single large step over Death Star, at each position a small 4-point sub-pixel dither box for full resampling of the PSF. Pre-defined pattern WFC3-IR-DITHER-BOX-MIN can be used as is for each of the two sub-pixel dither boxes. Use POSTARGs for the large move over Death Star with pixel offsets (-49.2, 49.7).

Table 4. Specifications of the D-patterns

	D2	D3	D4	D6	D8
Step 1	(0.0,0.0)	(0.0,0.0)	(0.0,0.0)	(49.2,-49.7)	(0.0,0.0)
Step 2	(-49.5,49.5)	(-49.33,49.33)	(-2.5,1.5)	(46.7,-48.2)	(4.0,1.5)
Step 3		(-98.66,98.66)	(-49.2,49.7)	(0.0,0.0)	(2.5,4.0)
Step 4			(-51.7,51.2)	(-2.5,1.5)	(-1.5,2.5)
Step 5				(-49.2,49.7)	(-49.2,49.7)
Step 6				(-51.7,51.2)	(-45.2,51.2)
Step 7					(-46.7,53.7)
Step 8					(-50.7,52.2)

E-patterns

These patterns are constructed to move over the IR blobs by using ~40 pixel step. Steps are done in diagonal towards upper left to avoid overlap of bad regions. Additional small sub-pixel steps are constructed to recover the PSF.

- E2: A single large step over IR blobs. Pre-defined pattern WFC3-IR-DITHER-LINE can be used if modified.
- E3: Two large steps over IR blobs. Pre-defined pattern WFC3-IR-DITHER-LINE-3PT can be used if modified.
- E4: A single large step over IR blobs with an additional small sub-pixel step at each position to sample the PSF. Pre-defined pattern WFC3-IR-DITHER-BOX-MIN can be used if modified.
- E6: Two large steps over IR blobs, each with additional small sub-pixel steps to

sample the PSF. No existing pattern.

- E8: A single large step over IR blobs, at each position a small 4-point sub-pixel dither box for full resampling of the PSF. Pre-defined pattern WFC3-IR-DITHER-BOX-MIN can be used as is for each of the two sub-pixel dither boxes. Use POSTARGs for the large move over IR blobs with equivalent pixel offsets (-28.2, 28.7).

Table 5. Specifications of the E-patterns

	E2	E3	E4	E6	E8
Step 1	(0.0,0.0)	(0.0,0.0)	(0.0,0.0)	(28.2,-28.7)	(0.0,0.0)
Step 2	(-28.5,28.5)	(-28.33,28.33)	(-2.5,1.5)	(25.7,-27.2)	(4.0,1.5)
Step 3		(-56.66,56.66)	(-28.2,28.7)	(0.0,0.0)	(2.5,4.0)
Step 4			(-30.7,30.2)	(-2.5,1.5)	(-1.5,2.5)
Step 5				(-28.2,28.7)	(-28.2,28.7)
Step 6				(-30.7,30.2)	(-24.2,30.2)
Step 7					(-25.7,32.7)
Step 8					(-29.7,31.2)

F-patterns

The F-patterns include small step dithers that do not step over IR blobs. Preferentially used for targets of limited spatial extent. Place the target outside currently known blobs. A subarray may be used. Sub-pixel steps are constructed for an optimal PSF reconstruction.

- F2: A single small step. Pre-defined pattern WFC3-IR-DITHER-LINE can be used as is.
- F3: Two small steps in a line. Pre-defined pattern WFC3-IR-DITHER-LINE-3PT can be used as is.
- F4: Small dither steps in a 4-point box pattern. Pre-defined pattern WFC3-IR-DITHER-BOX can be used as is.
- F6: Similar to F3, but with an additional ½ pixel steps in x-direction at each position. No pre-defined pattern.
- F8: Two small 4-point box patterns are offset by ¼ sub-pixel steps for optimum 8-point PSF resampling. Pre-defined pattern WFC3-IR-DITHER-BOX can be used as is for each of the two sub-pixel dither boxes. Use POSTARGs with equivalent pixel offsets (2.75, 2.75) for the sub-pixel shift between the box patterns.

Table 6. Specifications of the F-patterns

	F2	F3	F4	F6	F8
Step 1	(0.0,0.0)	(0.0,0.0)	(0.0,0.0)	(0.0,0.0)	(0.0,0.0)
Step 2	(3.5,3.5)	(3.33,3.33)	(4.0,1.5)	(2.5,1.0)	(4.0,1.5)
Step 3		(6.66,6.66)	(2.5,4.0)	(3.33,3.33)	(2.5,4.0)
Step 4			(-1.5,2.5)	(5.83,4.33)	(-1.5,2.5)
Step 5				(6.66,6.66)	(2.75,2.75)
Step 6				(9.16,7.66)	(6.75,4.25)
Step 7					(5.25,6.75)
Step 8					(1.25,5.25)

How to construct patterns in the APT

In order to use the offsets given in pixels above in the APT, these have to be converted into distances in arcsec and orientations of the patterns in degrees. For the UVIS channel, the distances in arcsec are related to x and y in pixel coordinates by:

$arcsecX = a_{11} * x$

$arcsecY = b_{11} * x + b_{10} * y$

where a_{11}=0.03962 arcsec/pix, b_{11}=0.00272 arcsec/pix, and b_{10}=0.03953 arcsec/pix in the pre-flight SIAF (Science Instrument Aperture File). The cross-term b_{11} takes into account the non-perpendicular projection of the UVIS axis. For the IR channel, the relations are:

$arcsecX = c_{11} * x$

$arcsecY = d_{10} * y$

where c_{11}=0.1355 arcsec/pix and d_{10}=0.1211 arcsec/pix. (Here we have chosen to call the IR coefficients “c” and “d” instead of the nominal “a” and “b” to avoid confusion). Note that due to the geometric distortion, these relations are accurate only at the center of the detectors. Furthermore, arcsecX and arcsecY are equivalent to POSTARGX and POSTARGY, therefore, these relations can be used to calculate the telescope shifts if POSTARGs are used instead of pre-defined patterns. To show how to use these relations when constructing patterns in the APT, we use two examples for each of IR and UVIS, respectively. The first pattern is a simple line pattern, while the second is a box pattern. These examples can be used to construct a majority of the patterns listed above.

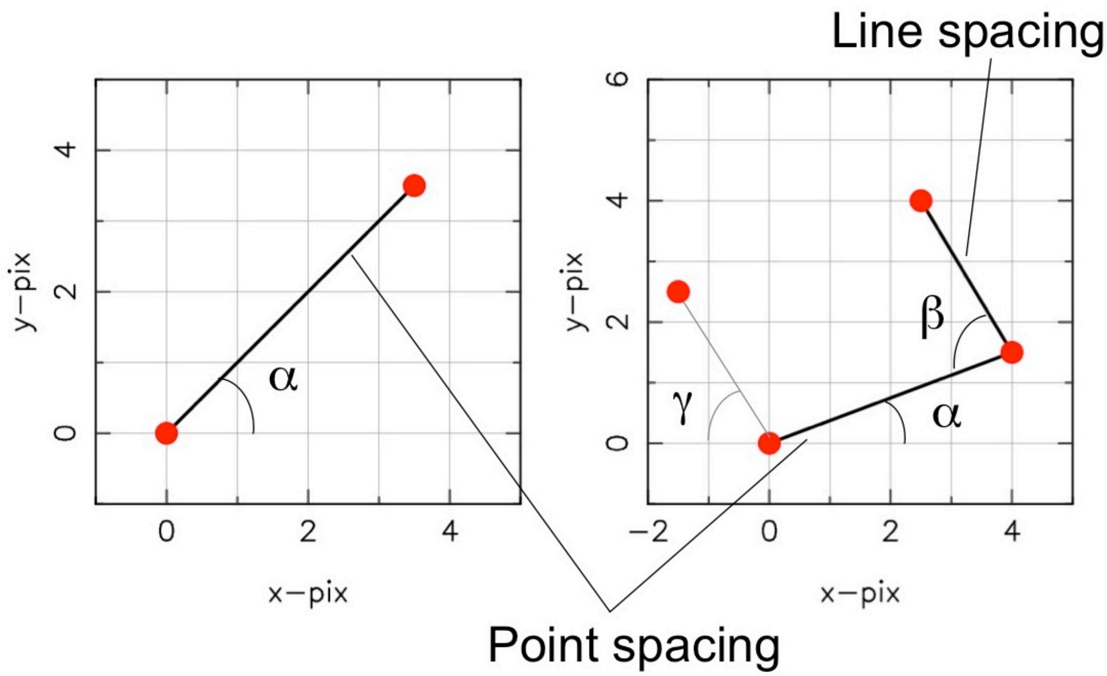

Figure 6. Definitions relating the x-y pixel coordinate system with the quantities required for creating dither patterns in the APT. The left panel shows a LINE pattern while the right panel shows a BOX pattern. (The angles are actually measured with respect to the orthogonal POSTARGX and POSTARGY axes. The y-pix axis and POSTARGY axis are aligned; the x-pix axis is rotated from the POSTARGX axis if b_{11} is non-zero.)

Example 1 – LINE pattern

In order to specify a LINE pattern two quantities have to be specified, besides the number of points in the line. First the "Point spacing" gives the distance in arcsec between points, and second, the "Pattern Orient" gives the angle (α) between the line and the POSTARGX axis. See Figure 6 for definitions. For UVIS and IR we construct 2-dither patterns with pixel coordinates (0.0,0.0), (2.5,2.5) and (0.0,0.0), (3.5,3.5), respectively.

<u>UVIS</u>

Point spacing = $\mathrm{sqrt}([2.5*a_{11}]^2+[2.5*b_{11}+2.5*b_{10}]^2)$ = 0.145 arcsec

Pattern orient (α) =$\arctan[(2.5*b_{11}+2.5*b_{10})/(2.5*a_{11})]$ = 46.840 degrees

<u>IR</u>

Point spacing = $\mathrm{sqrt}([3.5*c_{11}]^2+[3.5*d_{10}]^2)$ = 0.636 arcsec

Pattern orient (α) = $\arctan[(3.5*d_{10})/(3.5*c_{11})]$ = 41.788 degrees

Example 2 – BOX pattern

In order to specify the BOX patterns, four quantities are needed. First the "Point spacing and “Patterns Orient” as defined above are required. In addition, a “Line Spacing” and an “Angle between Sides” have to be specified. See right panel of Figure 6 for definitions. In the figure, the “Angle between Sides” is denoted by β. For UVIS and IR we construct BOX patterns with the same coordinates (0.0,0.0), (4.0,1.5), (2.5,4.0), and (-1.5,2.5).

<u>UVIS</u>

Point spacing = sqrt($[4.0*a_{11}]^2+[4.0*b_{11}+1.5*b_{10}]^2$) = 0.173 arcsec

Pattern orient (α) =arctan$[(4.0*b_{11}+1.5*b_{10})/(4.0*a_{11})]$ = 23.884 degrees

Line spacing = sqrt($[-1.5*a_{11}]^2+[-1.5*b_{11}+2.5*b_{10}]^2$) = 0.112 arcsec

Angle between sides (β) = $\alpha + \gamma$ = 23.884 + arctan$[(-1.5*b_{11}+2.5*b_{10})/(1.5*a_{11})]$ = 23.884 + 57.901 = 81.785 degrees

<u>IR</u>

Point spacing = sqrt($[4.0*c_{11}]^2+[1.5*d_{10}]^2$) = 0.572 arcsec

Pattern orient (α) = arctan$[(1.5*d_{10})/(4.0*c_{11})]$ = 18.528 degrees

Line spacing = sqrt($[1.5*c_{11}]^2+[2.5*d_{10}]^2$) = 0.365 arcsec

Angle between sides (β) = $\alpha + \gamma$ =18.528 + arctan$[(2.5*d_{10})/(1.5*c_{11})]$ = 18.528 + 56.125 = 74.653 degrees

Comments on coefficients

The coefficients used above, derived by modeling, are the ones that were used to compute the parameters in the WFC3 convenience patterns in APT. The coefficients have been re-derived using on-orbit observations. The changes in the coefficients are marginal and will not cause any significant changes in the shifts. The coefficients are valid at the center of the two detectors and vary slightly with position due to the non-linear geometric distortion. In Table 7 we give the model and measured coefficients (from the April 2010 SIAF) for the centers of the two detectors and for the center of the UVIS1 and UVIS2 chips separately. (For IR, a=c and b=d if using the same notation as above.)

Table 7. Coefficients for transforming pixel coordinates to distances in arcsec

UVIS: model vs measured (April 2010)

	model UVIS	measured UVISCTR	measured UVIS1FIX	measured UVIS2FIX
a11	0.03962	0.03966	0.03954	0.03978
b10	0.03953	0.03959	0.03936	0.03984
b11	0.00272	0.00261	0.00270	0.00250

IR: model vs measured (April 2010)

	model IR	measured IRFIX
a11	0.1355	0.1354
b10	0.1211	0.1209
b11	0.0000	0.0004

Summary

Dithering is important for mitigating the effects of bad pixels and other detector artifacts, to minimize the effect of pixel-to-pixel variations in the flat-field, to recover spatial information lost due to under-sampling, and to exclude pixels hit by cosmic rays. In this report we have discussed specific dithering strategies for the UVIS and IR channels on WFC3. To help choose dither strategy in different situations, we have presented a number of recommended dither patterns. Our main conclusions are:

- A rule-of-thumb is to use as many dithers as possible while still achieving the required signal-to-noise. Two or three dither positions may be sufficient, but four positions are often desired.
- Sub-pixel dithers are needed to resample the PSF. An optimized 4-point dither pattern recovers the "full" information of the PSF, while a 2-point or 3-point pattern recovers some of the information.
- Due to geometric distortion, large dither steps have to be combined with small step sub-patterns if PSF resampling is important.
- The number of dither steps needed to effectively exclude cosmic ray hits depends on exposure time. Two steps may be sufficient for short exposures (<1000s), while at least four steps are recommended for long exposures (>1800s). Cosmic rays only affect the UVIS channel.

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