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The Impact of Spacecraft Jitter on STIS Coronagraphy

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ABSTRACT

Between 21-April 2018 and 5-October 2018 the combination of gyroscopes 2,4, and 6 resulted in a higher than normal spacecraft jitter that exceeded 15 mas in amplitude, with larger excursions possible. This amplitude of jitter was predicted to present noticeable degradation to the contrast performance of the STIS coronagraphic apertures and thus a special calibration program was executed on 23-September 2018 to assess the impact. We find that higher levels of jitter increase a systematic component to the noise within a set of coronagraphic images, impacting contrast performance. We review our current recommendations on when jitter reaches a level that could impact specific scientific cases.

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Introduction

STIS is the only operating instrument on Hubble that possesses a coronagraph capable of obtaining high contrasts at small angular separations. The origin of this ability for high contrast lies in the relative stability of the observatory compared to ground-based telescopes. At small angular separations the contrast achievable by STIS is primarily limited by non-Gaussian noise likely caused by a combination of slowly varying wavefront aberrations and telescope jitter (Debes & Ren, 2019; hereafter DR19). The achievable contrast one could obtain of a given star is thus impacted by the instantaneous jitter experienced during a given set of observations. For the majority of the Hubble Space Telescope's history, spacecraft jitter has been measured to have a root sum of squares (RSS) over one minute of ~3 mas or less. During the period of 21-April 2018 and 5-October 2018, the combination of gyros 2,4, and 6 resulted in a heightened amount of jitter that approached an amplitude of 15-20 mas on average, with larger excursions possible over short periods of time, until Gyro 2 failed in October 2018.

DR19 demonstrated that a fundamental limit to contrast performance could be measured by taking the root mean square (RMS) noise as a function of angular radius from the star over a series of short exposures. If one knows the expected noise from the detector as well as photon shot noise from the wings of the stellar point spread function (PSF), one can estimate the noise contribution from residual speckles based on any excess in the RMS measures. The increased jitter motivated the STIS team to propose a special calibration program for Cycle 25 that investigated the impact that jitter may have on coronagraphic performance under the program number 15603, "STIS Coronagraphic Monitor".

During the epoch of increased jitter, the majority of the jitter was along the V2 direction in the observatory frame of reference (Osten, 2018). The STIS CCD detector is roughly aligned at a 45° angle relative to this frame, which means that the jitter roughly equally impacts coronagraphic apertures that are aligned along the detector X-axis and the detector Y-axis.

Observations

Program 15603 revisited the stellar target HD 38393, a nearby solar-type star that was bright enough to take short exposures with sufficient depth to reach high contrasts at small angular radii. It was previously used to investigate the contrast performance of the BAR5 occulter in the program 14426 (DR19). Program 15603 replicated the basic observing strategy of 14426 by executing a single orbit coronagraphic visit on 23-September-2018. A total of 96 CCD readouts with 0.2s exposure times were taken over a 1024x90 pixel subarray to minimize read out times and ensure no saturation at the edges of the mask. The BAR5 aperture location of 50CORON was selected to investigate contrast performance at small angular radii, since this is where the impact to performance should be greatest. In addition to the BAR5 observations, four WFC3/UVIS/F606W images of a parallel field were executed simultaneously in order to independently check the observed spacecraft jitter. The F606W filter was chosen to minimize impacts due to changes in focus during the orbit. Figure 1 shows an example cosmic-ray cleaned logarithmic image of one 0.2s exposure of HD 38393 as part of 15603 and 14426.

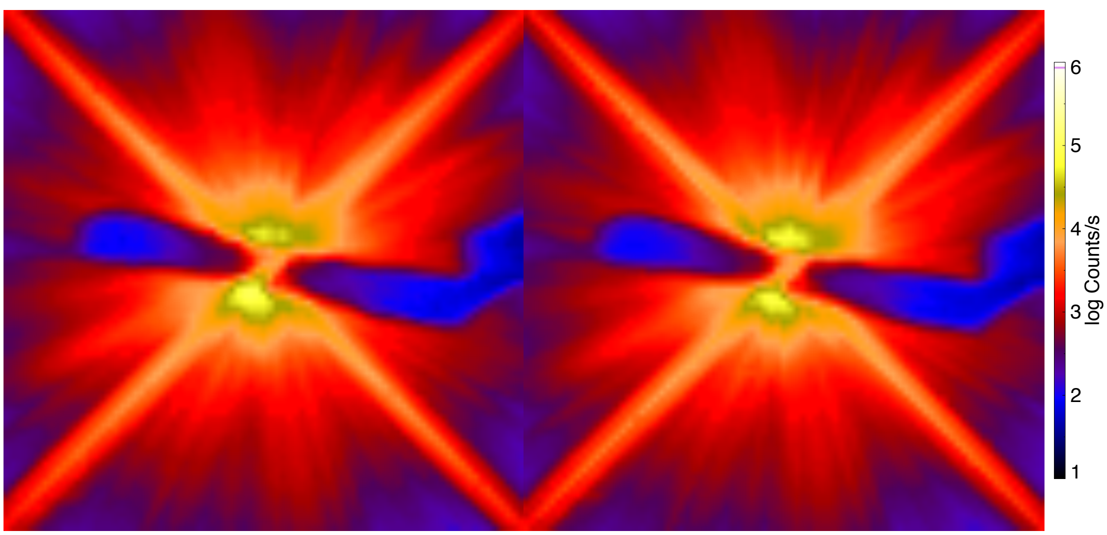

Figure 1: (left) Logarithmic image in counts/s of HD 38393 behind the BAR5 mask for a 0.2s exposure during Program 14426. (right) Logarithmic image of HD 38393 for a 0.2s exposure during Program 15603.

Analysis

Using the data from 15603 and comparing it to 14426, we measured the instantaneous jitter observed at the STIS/CCD focal plane simultaneously with an exposure averaged measure of the jitter at the WFC3/UVIS focal plane and that measured by the FGS. Further, we investigated how the increased jitter impacted raw contrast performance at BAR5. In the following discussion, we define detector-X to refer to the horizonal direction of the CCD and detector-Y as the vertical direction of the CCD (Hartig et al., 2019). Detector-Y is roughly aligned with the WEDGEA and BAR10 masks, while Detector-X is aligned with the WEDGEB mask. BAR5, due to the fact that it was bent during fabrication of the instrument, is aligned at an angle to both axes.

Jitter Measurements in STIS Data

Typically, HST instrument data is accompanied by jitter files as measured by the observatory telemetry. However, in cases where exposure times are less than three seconds (the typical timescale over which jitter information is averaged) jitter files are not created for a given data association. In order to measure the instantaneous jitter at the STIS focal plane, we employed a method for measuring the stellar centroid behind the BAR5 mask as described in DR19. Briefly, each diffraction spike peak was measured as a function of detector-X position. Under the assumption that the diffraction spikes all linearly connect to the central position of the star, one can solve for the centroid. We measured the instantaneous stellar centroid for each of the 96 exposures in Program 15603 and in the 881 exposures of Program 14426. Figure 2 shows a comparison of the centroids relative to the median detector position of the star within each visit for both programs. Note that in 14426, nine separate dither positions were executed within each orbit so for each dither position the average stellar position was calculated from the ten individual exposures taken within each orbit. The RSS jitter over the set of 15603 observations is 12.0 mas in detector-X coordinates and 10.9 mas in detector-Y coordinates, implying an amplitude of 16.2 mas. Over the three separate visits of 14426, the RSS jitter over the visits was 2.4 mas in detector-X and 2.4 mas in detector-Y, for an amplitude of 3.4 mas, with an average RSS amplitude of 2.9 mas.

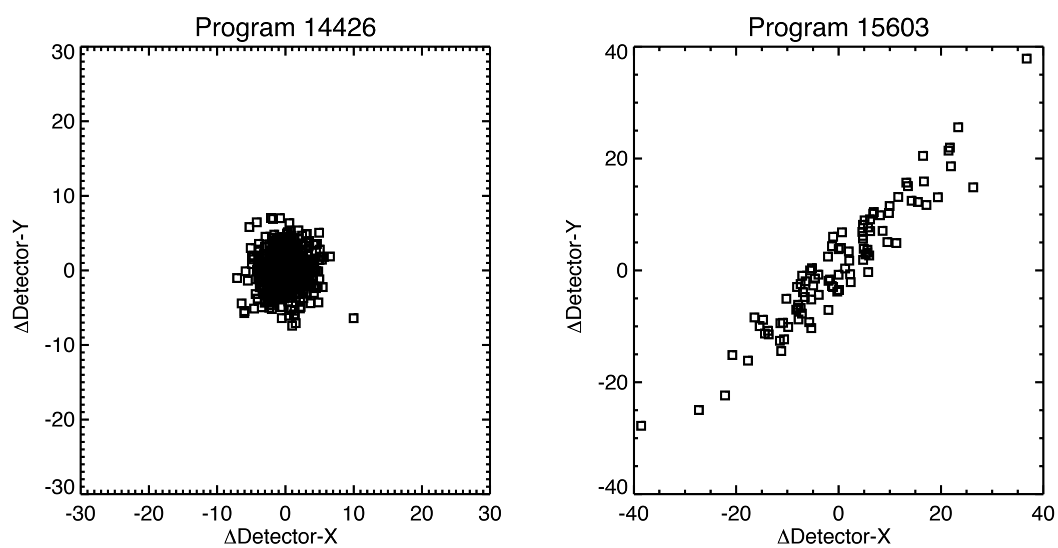

Figure 2: Comparison between measured centroids in a given coronagraphic exposure relative to the median stellar centroid for Program 14426 (left) and Program 15603 (right)

Jitter Measurements in WFC3 Data

Jitter in the WFC3/UVIS data was measured using the technique first developed in Anderson & Bedin (2017) and reported on in Anderson (2018) and Anderson & Sabbi (2018). This technique takes empirically determined models of the WFC3 PSF at a variety of focus states and convolves them with Gaussians representing various amounts of jitter and compares them to point sources in a given observation to determine the optimal focus and jitter for each exposure. Both measures of the focus and the jitter are made on the CTE-corrected images. In each image at least twenty stars were used to conduct the measurements. In all cases the PSF optimized for jitter and focus produces a qfit metric (a measure of the relative departure of a star image from the adopted PSF model) that is less than 0.04, which is typical of jitter-free stars. Given the longer exposure times, this provides an exposure averaged measure of the jitter throughout the orbit at the UVIS focal plane. Table 1 gives the results from the UVIS analysis. The mean of all the measures for the magnitude of the jitter is 16.1 mas.

Exposure	N_{stars}	QFit	Jitter (mas)	σ-Jitter (mas)
idw901jhq	20	0.037	15.9	1.0
idw901k3q	20	0.029	18.4	0.7
idw901l0q	21	0.033	14.6	1.3
idw901loq	21	0.034	15.5	0.7

Table 1: Table of jitter measurements in the WFC3/UVIS/F606W observations

Jitter Measurements from FGS Telemetry

Figure 3 shows the RSS jitter in the pointing over 1-minute intervals as measured by the Fine Guidance Sensors (FGS) between 21-April 2018 (Day of 112 2018) and 5-October 2018 (Day 279), when the 2,4, 6 gyro combination was active. During 23-September 2018 (Day 266) when Program 15603 executed, the average RSS value of the jitter was 15.7 mas. The jitter measurements from a variety of techniques and science instruments are all consistent with each other to within one mas.

Impacts to Contrast Performance

With the amplitude of the jitter firmly established, we now investigate what impact this may have on the limiting contrast possible at small angular radii. As demonstrated in DR19, the contrast floor of most observations at small angles is dictated by speckle noise, which tends to overwhelm the shot noise from PSF wings. STIS speckle noise appears to be due to a combination of focus variations and spacecraft jitter (DR19). For STIS, this speckle noise showed a consistent level and behavior between 2012-2015. DR19 broadly found that the speckle RMS pixel^{-1} followed a power-law decrease in power as a function of increasing angular radius, and that it did not deviate beyond a level of ~40%.

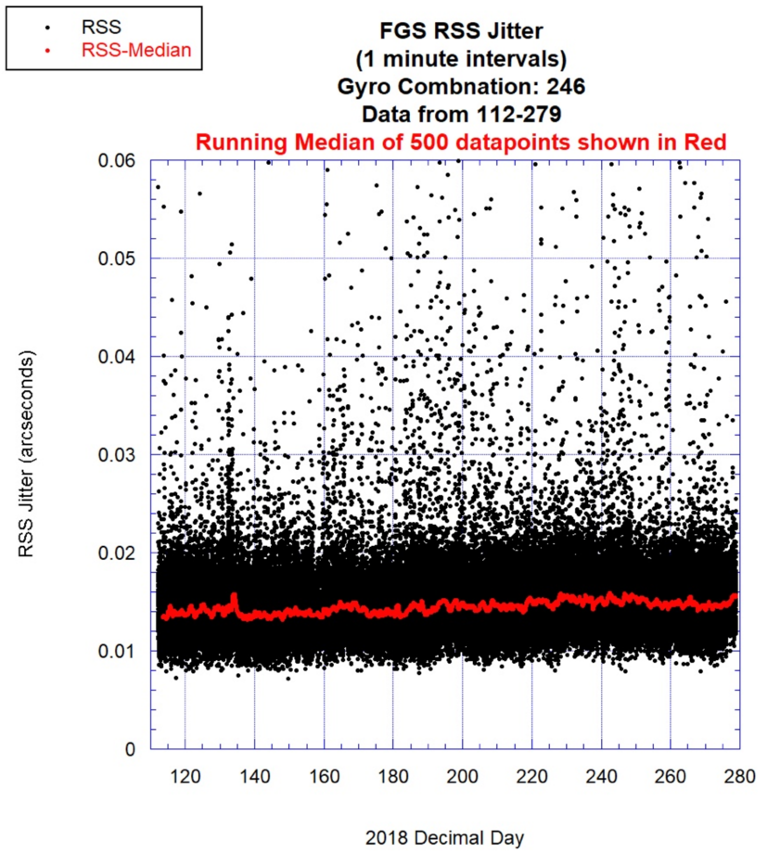

Figure 3: Measure of RSS jitter during the time period that the 2,4,6 gyro combination was active. The red curve denotes a running 500 point median which roughly corresponds to a 24-hour period of time.

We measured the RMS speckle noise following the methods outlined in DR19 for 14426 and the single orbit of 15603. Briefly, we measured the standard deviation of counts in each pixel of an image over the total number of exposures for a given visit of a program and azimuthally averaged the noise over regions not impacted by the 50CORON mask or the diffraction spikes of the star. We then calculated the expected noise in each pixel due to the detector and photon noise from the PSF wings and subtracted it off in quadrature from the observed noise, under the assumption that all excess noise arose from speckles. Figure 4 shows a comparison between the measured speckle RMS pixel^{-1} for both programs. The RMS is increased close to the mask edges, and particularly nearest to the star. The speckle noise can be characterized by a power-law exponent and scaling factor. We constructed an average of each visit of 14426 as well as the orbit averaged noise of 15603. DR19 already showed that the residual noise could be fit by a curve of the form $C(r)^{-b}$, where C=1.3x10^{-3} and b=2.86, and where r refers to the radius in detector pixels. We find that the increased jitter results in more noise that can be characterized by a different power-law curve and scaling. The high jitter case is found to have *C*=0.03 and *b*=3.8. This could be further quantified for all coronagraphic programs taken with STIS to better constrain this trend as a function of jitter, though this is beyond the scope of this ISR.

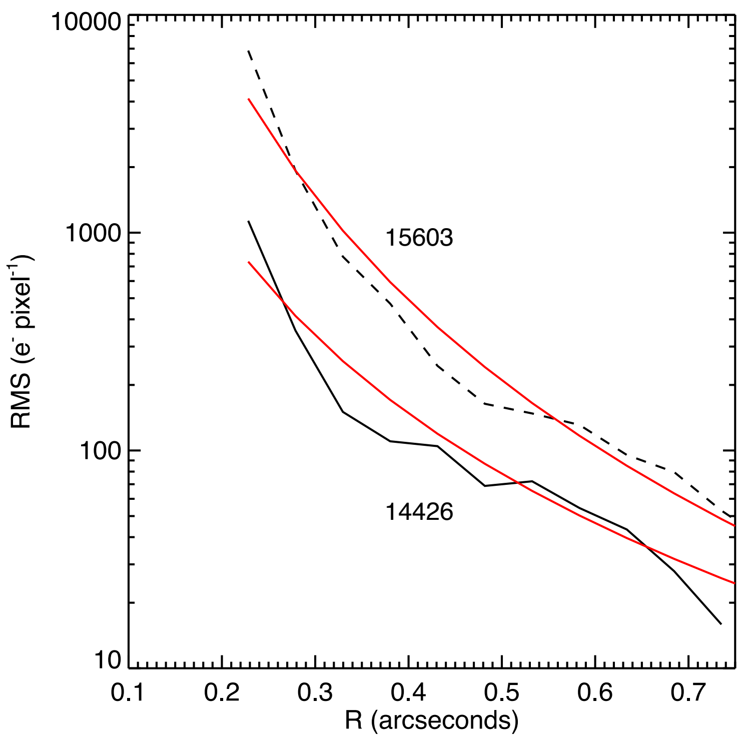

Figure 4: Measure of the residual speckle noise seen over the two coronagraphic programs 15603 (dashed line) and 14426 (solid line). The red curve denotes the best fit power-law relation fit for each program. The scale of the noise is related to a power-law curve and scaled by the peak brightness of the PSF, estimated to be 2.08×10^8 e^- $pixel^{-1}$ in a 1s exposure.

Recommendations

In general, the contrast at small inner working angles is degraded by increased spacecraft jitter. The noise from speckles is increased by a factor of at least two interior to 0.7" when the RMS jitter perpendicular to the coronagraphic mask is ~10-12 mas, implying a similar degradation in achieved contrast. Users should routinely check the latest jitter of the spacecraft to assess whether their science goals will be compromised by the jitter levels. Users can assess the impact from jitter on their existing observations by downloading associated jitter files from their programs (if available), or by using the stellar centroiding methods outlined in DR19. While the jitter has historically been quite stable over the lifetime of Hubble, the period of time when the gyro configurations of 2,4,6 and 3,4,6 have been active have shown increased spacecraft jitter over historical norms, which impacts the contrast achievable with STIS coronagraphy. Because the speckle noise is systematic, longer exposure times do not necessarily improve contrast close to the star. Therefore, users should inquire about the latest jitter behavior when designing their Phase II and should be aware when announcements about changes to observatory jitter behavior occur.

Acknowledgements

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Change History for STIS ISR 2019-04

Version 1: 3 December 2019 – Original Document

References

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