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Impact of Increased Jitter on WFC3/UVIS PSFs

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ABSTRACT

In the last few months, HST has experienced increased jitter in its pointing stability as some of its gyros have begun to experience performance issues. This ISR is a quick investigation to determine what level of jitter can be expected to cause problems for HST observations. We begin by examining how the nominal-jitter HST PSF varies spatially and temporally so that we can put any jitter-induced variations into perspective. We then simulate PSFs with various amounts of added jitter to determine at what amplitude jitter will impact sensitive high-precision measurements. We then take an empirical look at how the jitter experienced from early 2017 to the present has impacted PSF-based measurements. We find that the current level of jitter does have a noticeable effect on the PSF, but it does not yet have a significant impact on high-precision astrometric observations.

1. Introduction

In the last few months, HST has seen increased jitter in its pointing as one of its gyros has begun to experience stability issues. Although HST still does have three nominally functioning gyros (from the 6 that were installed in SM4) and could use them to improve the pointing immediately, the longer we can continue to use the degrading gyro, the longer we can extend the total lifetime of HST (including the overlap with JWST). Therefore, it is important to determine at what point jitter will begin to compromise HST's scientific productivity.

This study examines the impact of jitter on the WFC3/UVIS PSF. The results of this study will help the HST engineering team decide when it is best to switch off a degrading gyro (which will then likely be gone forever) and switch on a fresh gyro. It will also help users decide whether

they would prefer to delay observations that require particularly good pointing until a time when they can be taken with more stable pointing.

In this ISR we will examine the jitter as a function of time, focusing on the past year of operation. We will also study how we should expect jitter to affect the HST PSF in the context of the other PSF variations that are unavoidably present in HST images. We will then determine at what level the added jitter will begin to affect the kinds of high-precision science that can be routinely extracted from HST images. Finally, we will do an empirical investigation of recent HST images to make a direct evaluation of the precision that is possible.

2. Quantifying the increased jitter

The pointing information for each exposure is stored in the `jit` and `jif` files for each association of exposures. The `jif` files contain `fits` tables that report the pointing information for timeframes of several seconds throughout the course of each exposure. These files are particularly useful to help us evaluate how jitter might impact up-the-ramp fitting. The `jif` files, on the other hand, report sums over each exposure. For each exposure in the association, these multi-extension `fits` files contain a 2-d histogram image that reports the instantaneous pointing offset (with respect to nominal) for every 16th of a second during the entire exposure. The histogram bins are 2 mas on a side and contain a “1” for every time sample at the appropriate Δx , Δy offset.

Figure 1 below shows the `jif` histogram image for `ib4801qpj` taken in 2010 (on the left) and the histogram for `ida101smj` taken in Dec 2017 (on the right).

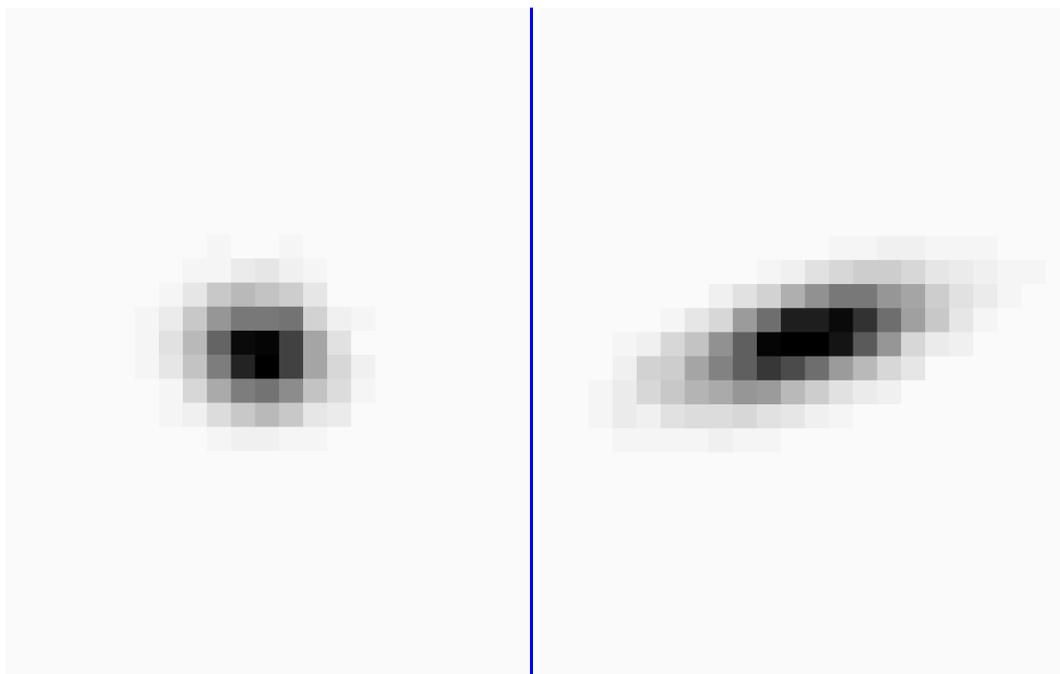


Figure 1: The raw 64×64-pixel `jif` images for two exposures. Each pixel is 2 mas on a side. The image on the left is from 2010, when jitter was nominal. The image on the right is from late 2017, when jitter was starting to become a concern.

To examine the jitter images in detail, we analyzed the jitter image for each of the ~6000 F606W exposures taken over the lifetime of WFC3/UVIS and determined the average and the RMS about that average along 4 different axes: 0 degrees, 45 degrees, 90 degrees, and 135 degrees. **Figure 2** shows the trends with time. Jitter is largely flat at about 3.5 mas per coordinate up until late 2016, at which point it slowly increases, largely in a direction that is somewhere between 0° and 45° (see the panels below).

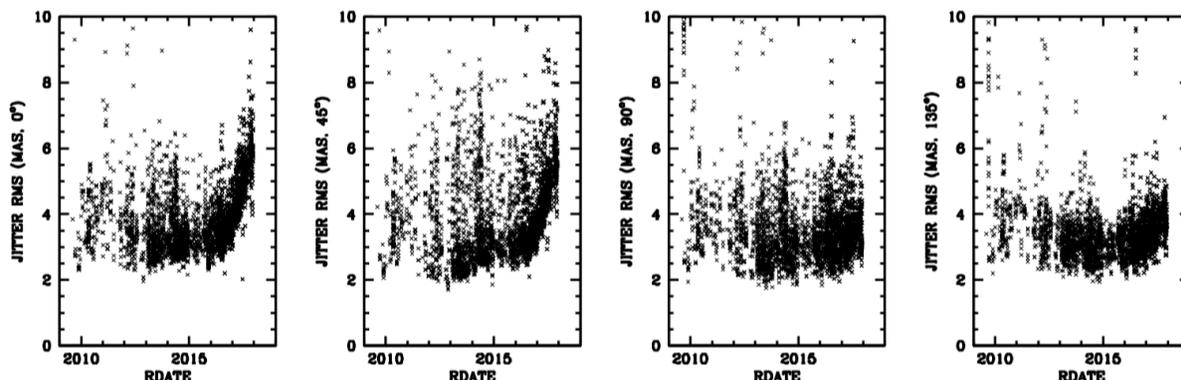


Figure 2: Distilled RMS along 4 axes of the `jif` jitter files for ~6000 F606W full-frame exposures.

3. WFC3/UVIS PSFs with Nominal Jitter

How much jitter can we tolerate before it starts to have a significant impact on the PSF? Of course, different scientific projects make different demands on the PSF. A project that does high-precision astrometry or PSF-subtracted crowded-field photometry will be more dependent on having a sharp PSF than will a project that is doing photometry on well separated objects or finding and measuring faint fuzzy galaxies. We will focus here on the most stringent requirements on the PSF: high-precision astrometry.

In order to put the impact of jitter into context, it is worth considering what the PSF looks like when the jitter is nominal. This will allow us to determine at what point jitter impacts the PSF more than the other issues that we cannot control.

The HST PSF is much more stable than any PSF on the ground. Yet even when jitter is its nominal best, the HST PSF is not a monolithic object, constant across space and time. The HST PSF varies quite a bit with both time and position. There are several ISRs that document the spatial and time variability of HST’s PSF (ISR 2016-12, ISR 2015-18, ISR 2014-24, and ISR 2013-11).

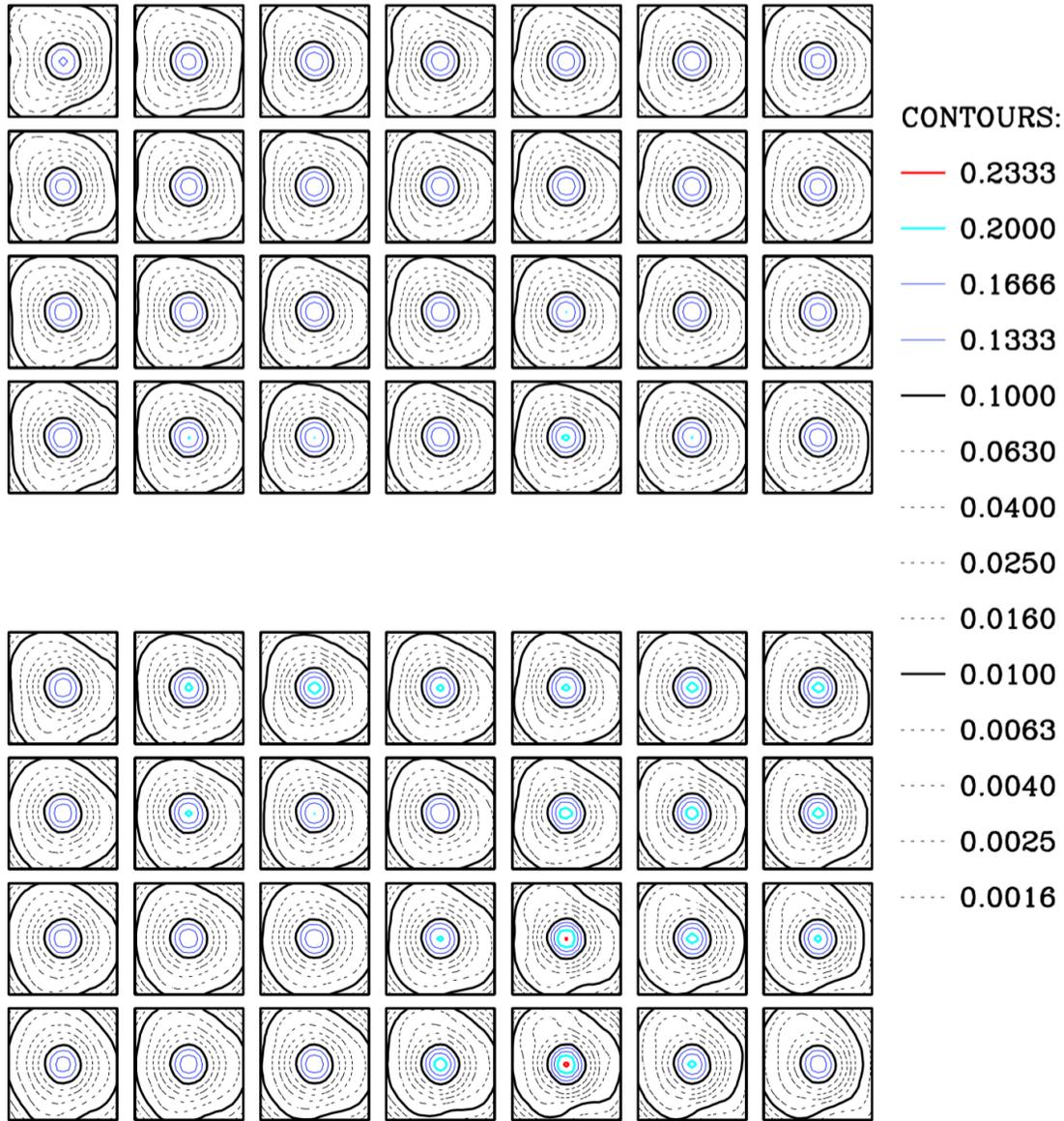


Figure 3: This figure shows how the inner 5×5 pixels of the F606W PSF vary with location on the detector. Each square panel represents roughly 500×500-pixel region on the WFC3/UVIS detector. Note the sharp “happy bunny” at the bottom of the detector towards the right (the only PSFs with red contours). This was first described in Sabbi & Bellini (ISR 2013-11).

3.1 Spatial variations

Figure 3 above shows how the inner 5×5 pixels of the PSF vary with location on the WFC3 detectors. When the PSF changes with location on the detector, there is a lot going on. It is not possible to distill all the spatial changes into a couple of moments, such as core-halo ratio, etc. This variation is caused by a variety of complex geometrical-optics effects and local chip phenomena (such as charge diffusion, see Krist ACS/ISR-2003-06). This variability cannot be avoided.

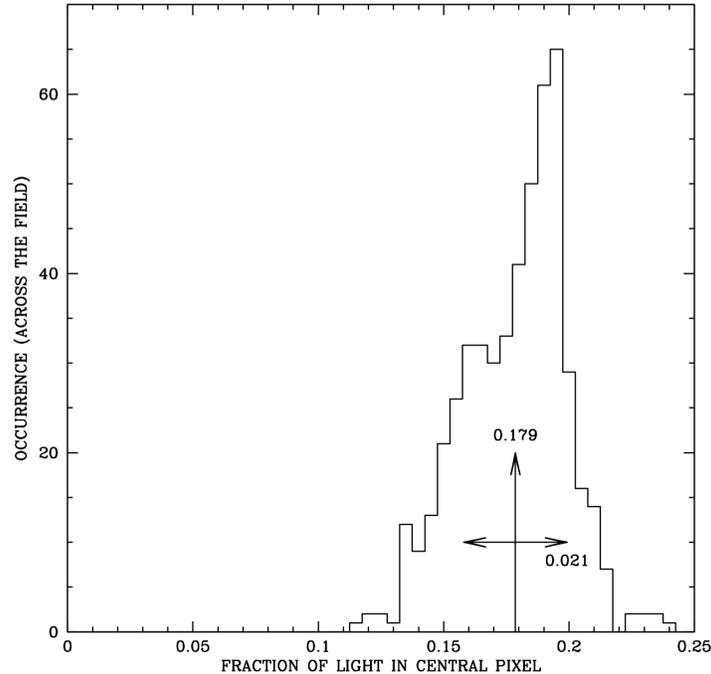


Figure 4: Histogram of central-pixel values for the spatial array of PSFs shown in Figure 3 for F606W. The average PSF gets 17.9% of its light in its central pixel, with a standard deviation of 2.1%.

While we cannot fully describe this variability with a few simple parameters, we can get a sense of how much the PSF changes by examining the fraction light that lands in the core. That is probably the aspect of the PSF that users care about the most, since it is directly related to the telescope’s effective resolution. The central values of these PSF models correspond to the fraction of a star’s light that will land in its central pixel if the star is centered on that pixel.

Figure 4 above shows a histogram of these central values for the PSFs shown in **Figure 3**. The average WFC3/UVIS F606W PSF gets 17.9% of its flux in its central pixel, but this can vary between 12% in the corners and 24% in the “happy bunny” region at the bottom right of the detector. From this analysis, then it would seem that so long as jitter does not change the fraction of light in the central pixel by more than about 10% in a fractional sense (and 2% in an absolute sense), then jitter is not the dominant factor in PSF quality.

3.2 Temporal variations

In addition to changing with location on the detector, the WFC3/UVIS PSF also changes considerably with time. Anderson & Bedin (2017) took the GO-12911 observations of M4, which consisted of several visits per month over the course of a year, and built up a detailed model of the variations of the F467M PSF. They found that the PSF varied along a single-parameter curve, which could be traced to instrument focus. They traced out this focus curve and determined the full spatially variable PSF for a set of 11 fiducial focus levels.

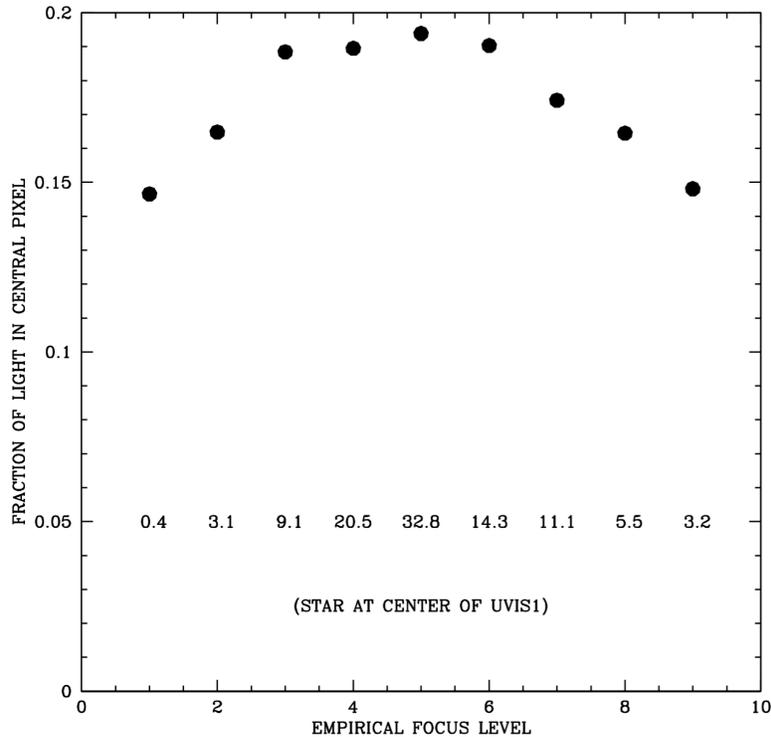


Figure 5: The fraction of light falling within a star’s central pixel for a star observed through F606W at the center of UVIS1, as a function of the empirical focus metric (see Anderson 2018, in prep). The numbers at the bottom give the fraction of F606W images characterized as having a particular focus.

While the empirical curve in Anderson & Bedin (2017) has not yet been calibrated in terms of mm of focus shift, it can nevertheless be used to determine an empirical focus measurement for a particular exposure, and then we can in turn determine an appropriate PSF for that exposure.

Anderson (2018, ISR in preparation) has generalized this study to construct focus-diverse PSFs from the entire WFC3/UVIS archive for the more common filters F275W, F336W, F435W, F606W, and F814W, along with F410M (the filter used by the engineering teams to monitor focus variations). The jitter issues have delayed this publication somewhat, since focus is no longer the only aspect of the PSF that must be considered: jitter must also be included.

Figure 5, based on data from Anderson (2018), shows the fraction of light that lands within the central pixel of a star at the center of the top chip (UVIS1) as a function of the empirical focus metric. The numbers at the bottom show the percent of exposures that are found to have a given focus level. More than 65% of the exposures have extracted focus values between 4 and 6, and for those exposures, the fraction of light at the center varies by about 0.01, which corresponds to a 5% fractional variation in the central intensity of the PSF.

When the PSF gets far out of focus, we see that the variation of the central intensity becomes much larger: about 15% of the exposures have relatively poor focus and subsequently have 0.03 less flux in the central pixel. This corresponds to a 15% fractional variation in the core intensity.

3.3 Evaluation of PSF models

It is worth considering how well the above PSF models describe real stars in real images. To explore this, we examined all of the full-frame F606W exposures in the archive. Even though there are not a lot of bright stars in the typical HST field, most images *do* have at least ~ 5 stars in them with a S/N of 30 or more, and it turns out if we have 5 or more stars, we can characterize the PSF in an exposure.

We went through each exposure, identified stars, and fit the PSF to each star. Fitting a star with the PSF involves first subtracting the sky using a local annulus (typically 8-12 pixels), then determining the optimum position and flux that minimizes the residuals between the model and the observed pixel values (typically the inner 5×5 pixels). These residuals can then be used to assess the quality of PSF model fit. Our `qfit` metric reports the absolute value of the residuals divided by the flux of the star. A value of “0.00” means a perfect fit between model and data. A value of 0.1 means that about 10% of the flux is inconsistent between observation and model.

We fit the stars with two different PSFs. In the first case, we used a simple constant-over-time library PSF, extracted from a particular set of images from a single visit that had nominal focus. In the second case, we used the focus-diverse PSF model to determine the optimal focus for each exposure from all the good S/N stars in that exposure. To do this, we tried a range of focus values from the minimum focus level to the maximum focus level and identified the optimal focus as the one that produced the minimum `qfit` metric for the image as a whole.

Figure 6 on the next page shows the results of this analysis. The top row shows the first case (the static nominal-focus PSF) and the bottom row shows the second case (the focus-flexible PSF). We find that if we use a spatially variable but temporally constant PSF to measure stars, about 50% of the time, our PSF fit quality is better than 0.05 (meaning there is only a 5% mismatch in the distribution of flux between observation and model). About 10% of the time the metric is worse than 0.10 and about 3% of the time it is worse than 0.15. However, if we determine an empirical focus for the exposure then use the appropriate PSF for the telescope’s particular breathing state, we find that almost *all* exposures can be fit to better than 5%.

From this we conclude that even with significant spatial and temporal variations, it is possible to measure the HST PSF quite accurately and thus do high-precision PSF-fitting science. It is therefore worth considering how increased jitter might jeopardize this capability.

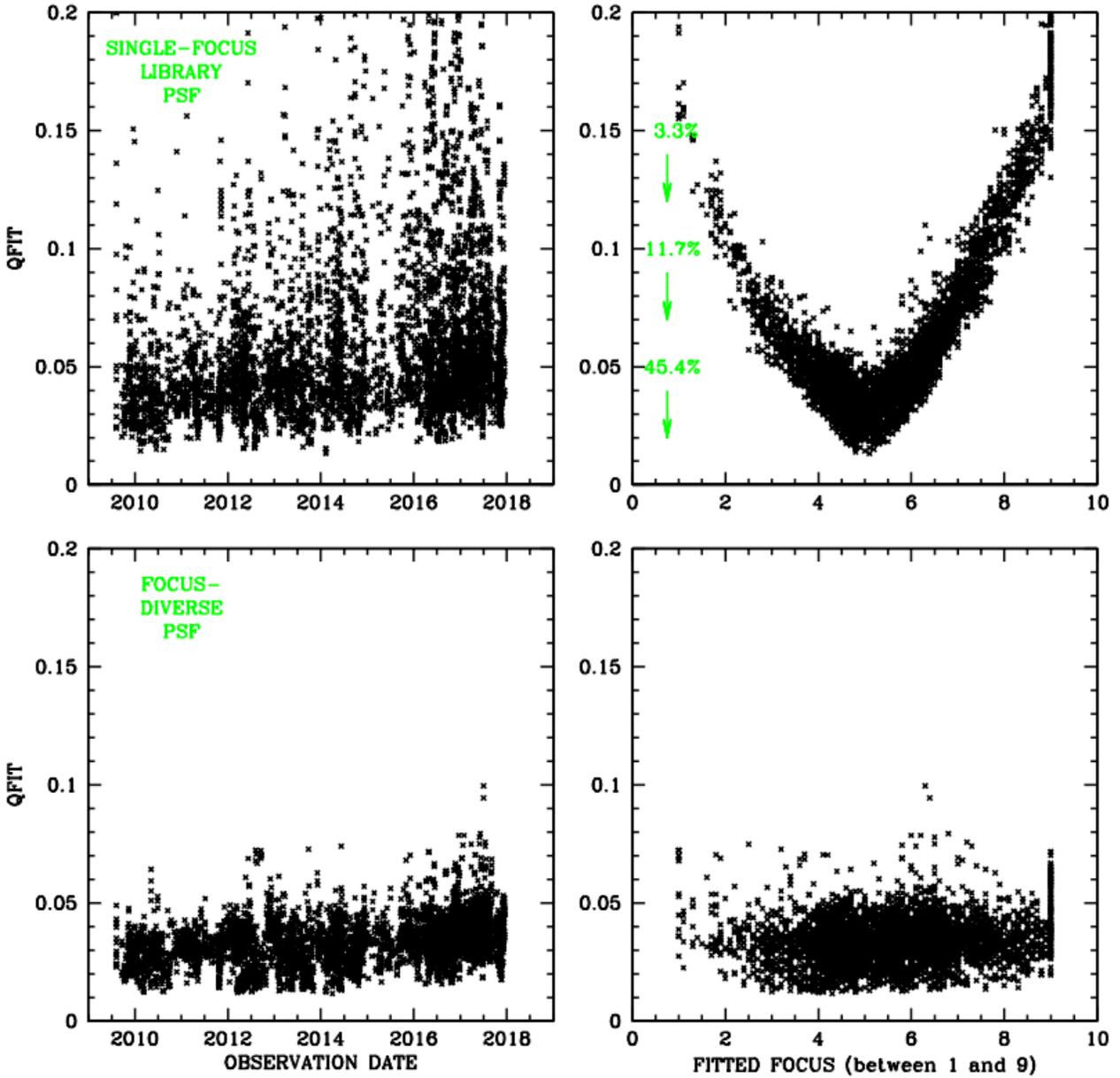


Figure 6: The vertical axis in all these plots show “ q_{fit} ”, an empirical metric that shows the total fractional disagreement between star images in individual exposures and the best-fit PSF model. The top panels show this metric for static PSF models, and the bottom panels show the metric for a focus-optimized PSF model. The left plots show the measure as a function of date, and the right plots show it as a function of fitted focus.

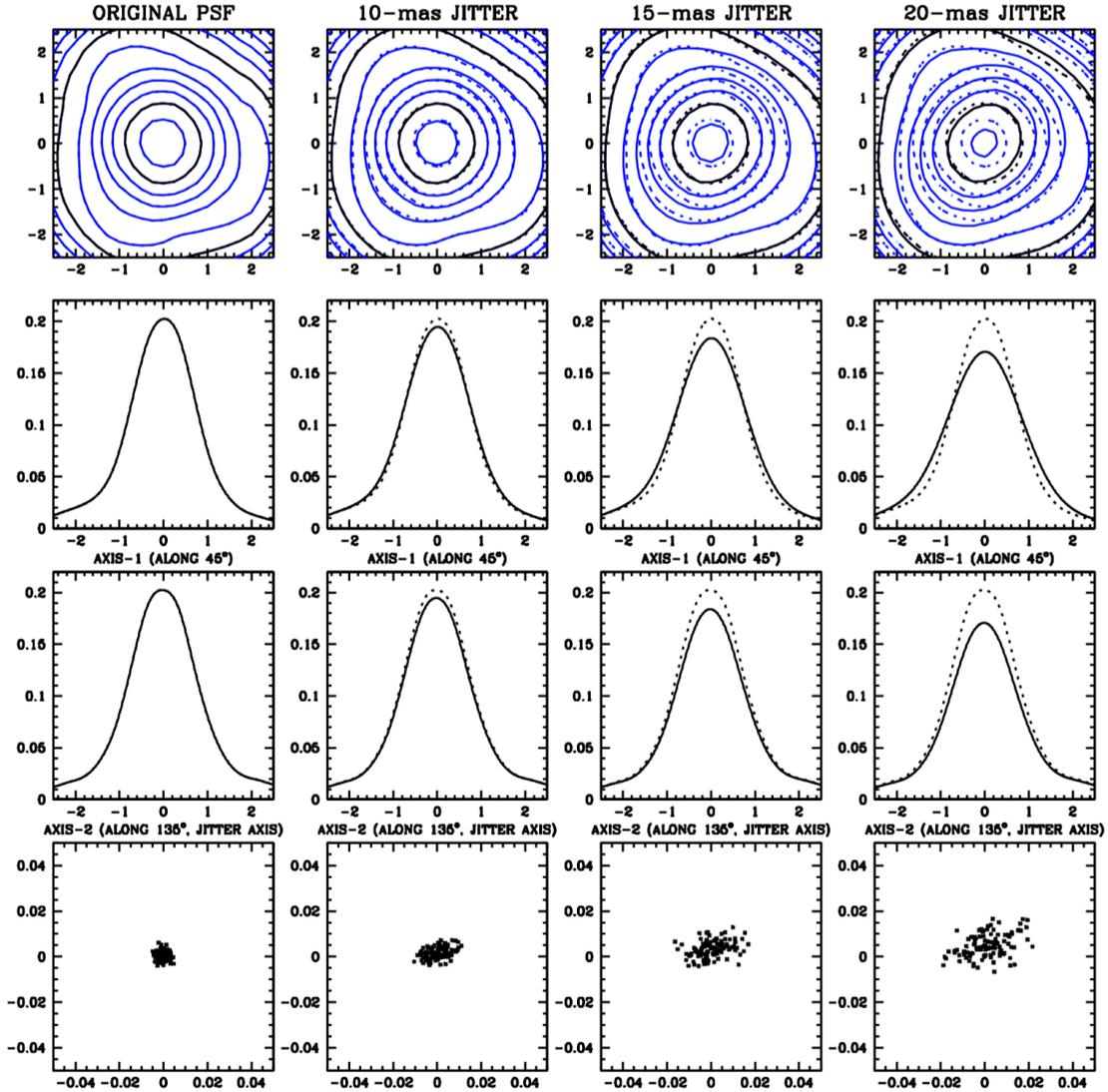


Figure 7: This plot shows the impact of adding jitter to the PSF model for a star observed through F606W at the center of the top chip (UVIS2). The top plot shows the PSF contours (solid with added jitter, dotted with nominal jitter). The jitter has been added at a 45° angle. The next two plots show slices along the 45° axis and along the 136° axis. The bottom row of plots shows the impact on fitting for the positions of stars.

4. What will increased jitter do to the PSF?

The PSFs that have been explored above are based on images that were taken with nominal jitter. The effect of this nominal jitter is implicitly included in the empirical PSF models. But it is possible to add additional jitter to the models to see what effect an increase of jitter might have on the PSF.

In Figure 7 above, we have taken a static PSF from the center of the UVIS2 chip and have added various amounts of jitter at a 45° angle relative to the detector coordinates. (This corresponds to

V3, which is the axis seen to have increased jitter from early 2017 to late April 2018.). The top plots show the contours of the new PSFs and the next two show slices along the jitter and anti-jitter directions. It is clear from the second row of plots that the PSF is broadened along the jitter axis, while the third row of plots shows that along the perpendicular axis, the PSF is simply scaled down with the FWHM remaining largely the same. We see that as we increase jitter from 0 to 10 mas, the fraction of light landing in the central pixel goes down by about 0.01. When we go up to 15 mas jitter, we get a loss of 0.02 and at 20 mas jitter, 0.03.

Jitter will naturally impact photometry by changing the fraction of light that lands in an aperture. If the aperture is wide, then a small amount of jitter will have a negligible impact on the result; but if the aperture is small (say, 5×5 pixels, an aperture that contains 80% of the relevant light), it can start to have a few-percent effect at jitters of 15 mas, which is similar to the impact of focus variations.

The bottom row of plots show the impact of jitter on astrometry. Astrometry makes much more stringent demands on the PSF than does photometry, so it is natural that we would expect to see the impact of increased jitter on the PSF first in astrometry. We inserted stars into a blank image with an enhanced-jitter PSF and measured them with the nominal-jitter PSFs. It is clear that in the bottom panels the errors increase roughly along the direction of jitter. It is worth noting that when we explored adding jitter along the x or y axes, the astrometric errors along that axis increase, while the other axis is largely unaffected. However, when jitter is added along orthogonal directions, the impact on astrometry is often less well confined to a single direction.

It makes sense that adding jitter along the x axis would make the FWHM of the PSF in the x direction wider than the model assumes. This will naturally introduce “pixel-phase errors” when the PSF is undersampled (see Anderson & King 2000). We find that errors are less than 0.005 pixel for 10-mas of jitter. This is largely undetectable, given that the typical empirical precision with a nominal PSF is 0.01 pixel. But when we get 15 mas of jitter, the jitter-related error is the same size as the usual measurement errors for a bright unsaturated star. When we get 20 mas of jitter, the jitter errors dominate.

It is also worth looking to see how the jitter-enhanced PSFs affect the `qfit` metric we have explored above for the real images. **Figure 8** on the next page shows the impact of various amounts of added jitter on the `qfit` parameter (measured by comparing the enhanced-jitter PSF against the nominal PSF in the same way as I compare actual star images against PSF models). Adding jitter up to 5 mas does not appear to affect the PSF much at all, but above this, the `qfit` parameter largely appears to vary linearly with jitter. Until we get an added jitter of 11 mas, the increased error in `qfit` is less than the 0.05 we typically see in our fits to actual stars in images. Once the jitter reaches 16 or so, the `qfit` will pretty much always be as bad as we see in the worst 10% of our current images.

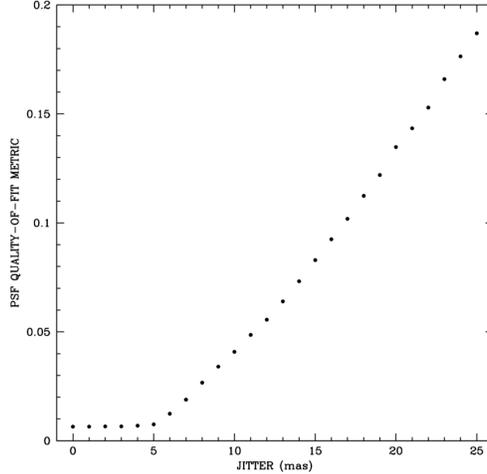


Figure 8: This shows the impact of jitter on `gfit`. We compared the jitter-enhanced PSF against the library PSF in the same way we compare star images against the PSF model in real images.

5. Examining Jitter in Observed Star Images

The previous sections have examined the jitter as measured by telemetry and have combined this with a theoretical study of how this might affect the PSF. We found that until jitter reaches a level of 11 mas, it will not significantly affect our ability to use a library PSF to analyze images. In this section, we will examine real images and examine jitter’s effect on the PSF and on astrometry directly.

We collected together all the full-frame F606W exposures taken between 2017 and the mid-May 2018 that had enough stars to study the PSF. We used the focus-diverse set of PSFs described above to determine the optimal focus (F) for each star in each exposure, but we also allowed for an empirical determination of the jitter (J). The focus level F was varied from 1 to 9, with steps of 0.1. The jitter was varied from -35 mas to 35 mas with steps of 1 mas, with negative jitter being along the 135D direction and positive jitter being along the 45D direction. We determined a best-fit value of F and J for each star in every exposure then found a robust average of the F and J values to determine empirically the average F and J for that exposure.

Figure 9 on the next page shows the results. The empirically determined focus varies between 1 and 9, with most exposures having nominal focus between 4 and 6. The jitter is found to increase from around zero in 2017 to around 8 mas in April 2018, at which point it immediately flips to around -12 mas (the flip of sign corresponds to a different major-axis direction).

STARS IN F606W IMAGES MEASURED SIMULTANEOUSLY FOR FOCUS & JITTER

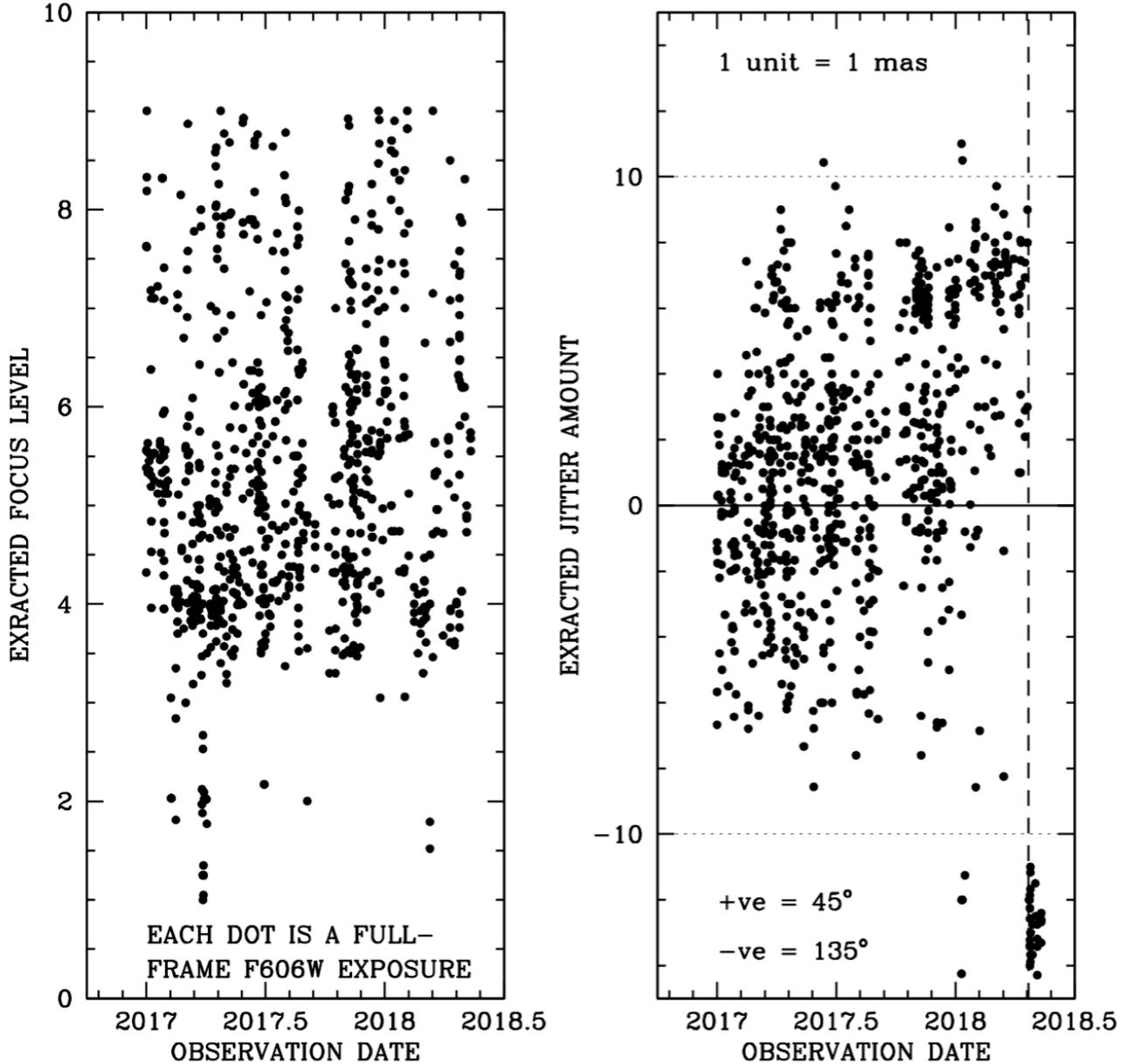


Figure 9: The left panel shows the empirically determined levels of focus for F606W images from 2017 through mid-2018 from fits to multiple stars in each exposure. The right panel shows the empirically determined jitter from the same fit. Positive jitter corresponds to a dispersion along the 45° direction, and negative jitter to a dispersion along the 135° direction. The vertical dotted line corresponds to the time of the gyro failure, when a new combination of gyros was used.

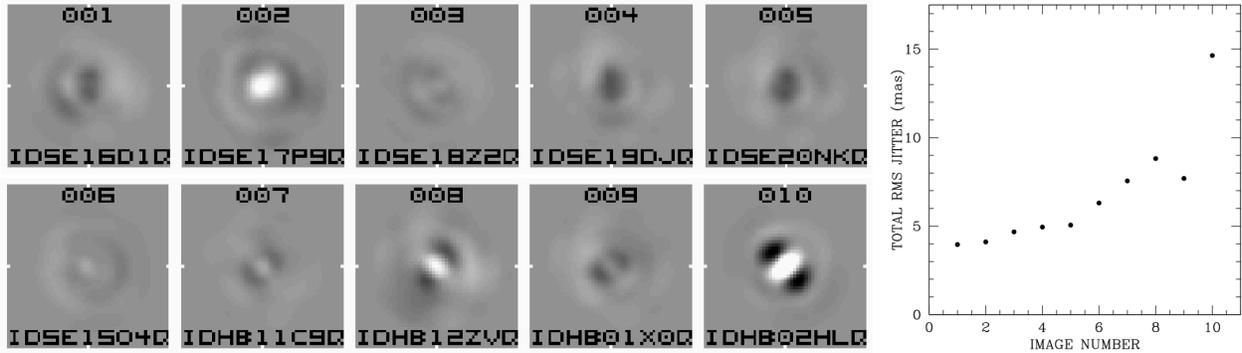


Figure 10: This shows the residual between the nominal F814W PSF and the PSF in each exposure for the middle exposure in ten visits, taken from late 2016 to the present, with the visits shown being taken 1-2 months apart. Black represents more flux, white less flux, with respect to the model PSF. In the 7th, 8th, and 9th panels, we see the PSF showing elongation roughly along the 45° direction, but in the 10th panel, we see the elongation along the 135° direction, consistent with the gyro reconfiguration. The total jitter for each of the ten exposures is shown on the right.

6. How Jitter Impacts Stellar Measurements

The jitter has clearly gotten progressively worse since early 2017. It is starting to enter the regime (> 11 mas) where astrometry should be able to notice increased errors.

To explore this, we reduced a set of images taken of the same open cluster (Westerlund-2, GO-14807 and GO-15362, both PI-Sabbi), which has been observed regularly from late 2016 when jitter was nominal to the present. The most recent observation is from May 2018, after the most recent gyro reconfiguration.

Figure 10 shows the residual PSF for 10 exposures from 10 different visits taken from late 2016 (upper left) through mid-May 2018 (lower right). This residual PSF is constructed by fitting the nominal PSF to stars throughout each exposure and distilling the many flux-normalized residuals into a single image. It is clear that exposure#2 is out of focus relative to the others. There is a symmetric redistribution of flux from the core to the inner halo. The residual PSFs of exposures #7 through #9 show broadening along the +45 degree direction, while exposure#10 shows even more broadening, but in the +135 degree direction.

We will examine the astrometry in the first visit and the last visit to determine how these PSF changes may affect measured quantities. Each visit consisted of six dithered F814W exposures. We reduced each exposure with the standard nominal-focus PSF and found the transformation between the distortion-corrected system of each exposure and that of the first exposure of the visit, which we used as the reference frame. We then collated the ~ 6 observations for each star in the reference frame and found an average position for each star. We then iterated the procedure once, using the new average positions as the reference frame and found a new average position for each star. We also recorded the RMS of the residuals about that average along each coordinate axis.

Figure 11 below shows the results for the nominal-jitter visit from late 2016 (images id5e16cxq through id5e16d7q). The top row of plots show the residuals of each exposure

with respect to the average for the bright stars with $S/N \sim 250$. All the images show a tight, circular distribution of residuals. The lower plots show the run of RMS residuals in x (middle) and y (bottom) against instrumental magnitude, where $m_{\text{inst}} = -2.5 \log_{10}(\text{flux})$. A star with an instrumental magnitude of -10 has a S/N of about 100. It is clear that the typical astrometric residual is about 0.005 pixel for the bright stars, with a natural increase as the S/N goes down. Both x and y exhibit the same residuals. This is typical of nominal-jitter behavior.

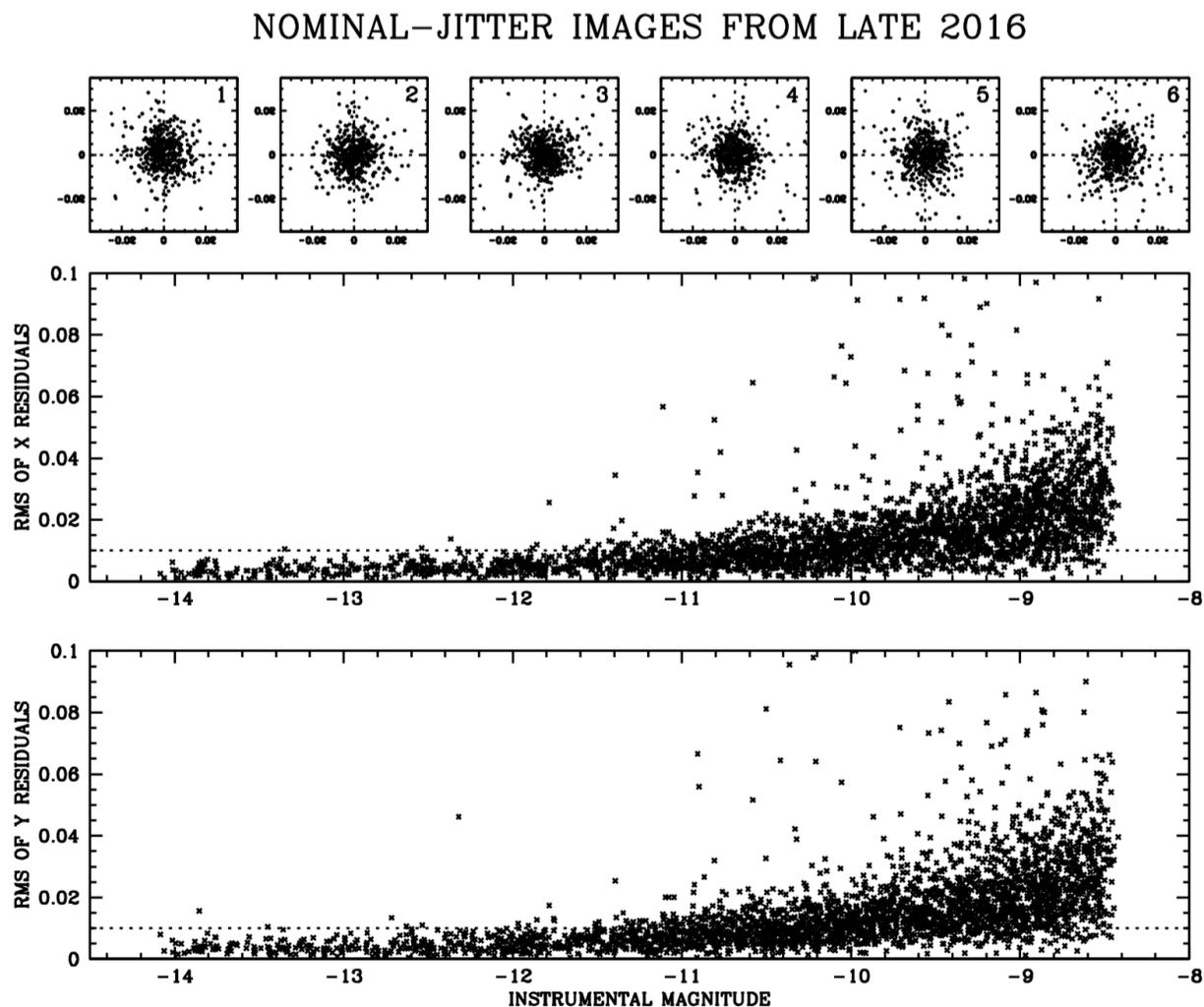
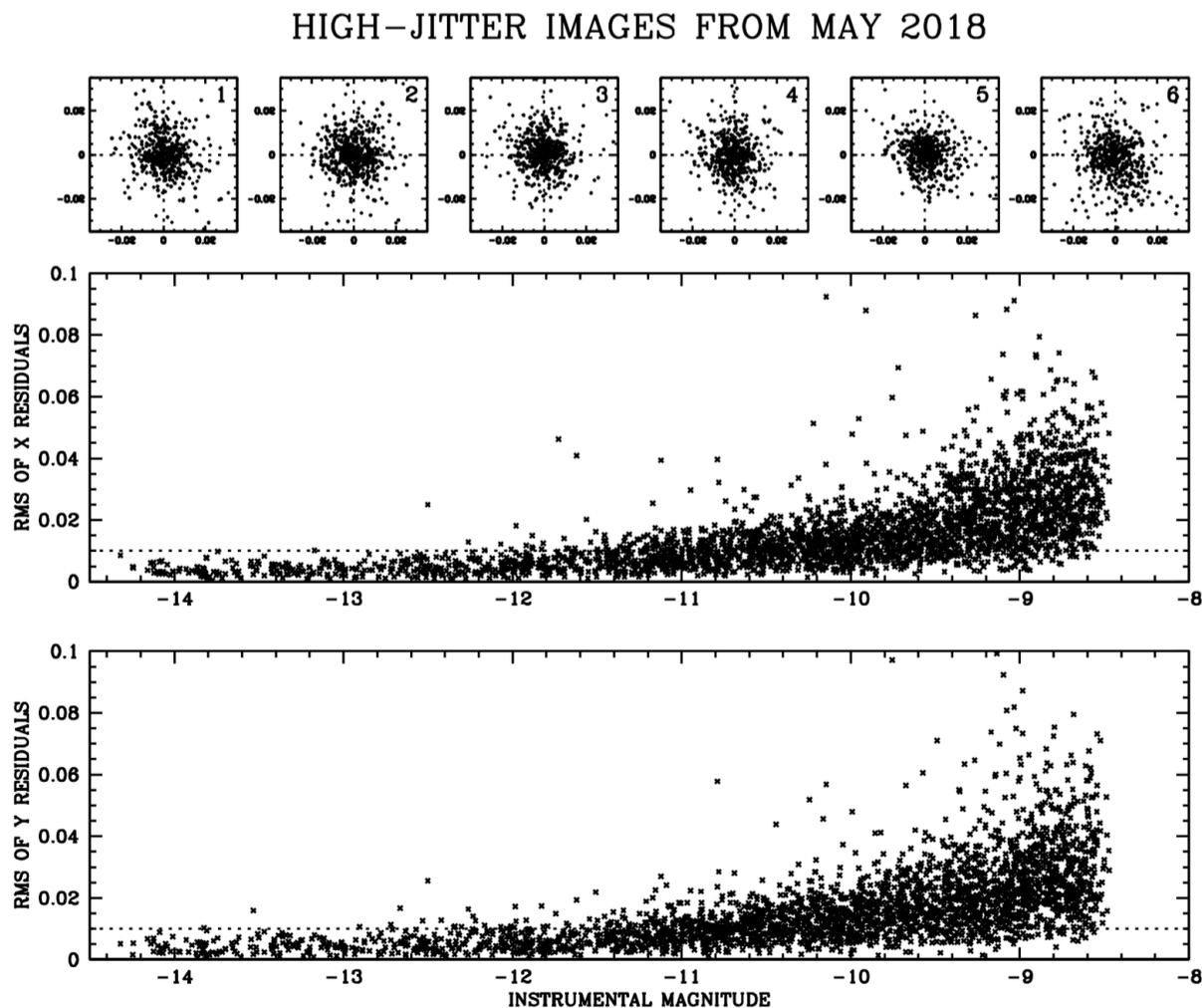


Figure 11: Top row shows the residuals for the $S/N \sim 250$ ($m_{\text{inst}} \sim -12$) stars between the position observed in each of the six exposures and the average position. The middle and bottom plots show the RMS of the six residuals for each star along the x and y axes, respectively. The dotted line is at 0.01 pixel.

Figure 12 below shows the same set of plots, but for a visit taken in mid-May 2018, after the most recent gyro reconfiguration. The images for this visit are `idhb02hhq` through `idhb02hrq`, and we used the same nominal-focus PSF to make the measurements as for the

other visit. Even with the increase of jitter beyond 10 mas, the residuals in the individual exposures look very similar to the residuals for the nominal-jitter visit shown in [Figure 11](#). Similarly, the residuals in x and y do not show much larger internal dispersion than in the nominal-jitter case. This is all very good news and gives us confidence that the increase in jitter has not yet compromised Hubble's measurement capabilities.



[Figure 12](#): Same as [Figure 11](#), but for a visit taken in May 2018, after the most recent gyro reconfiguration.

7. Conclusions and Future Plans

We have examined the impact of the increased jitter on PSF analysis and find that, thus far, the increase in jitter over the past year or so has not adversely impacted our ability to do high-precision science with WFC3/UVIS. We explored the theoretical impact of jitter on PSFs and determined that until jitter reaches 11 mas, there should be no noticeable impact, and it is not until it reaches 16 mas that jitter should be the dominant source of PSF variation.

We find that even with the increased jitter after the gyro reconfiguration in late April 2018, we can still use a “library” nominal-focus PSF to measure stars as accurately as we could in late 2016, when jitter was nominal. This gives us confidence that HST is still providing the exquisite image quality that we have been accustomed to.

The focus-diverse PSFs used here will be made available to the community shortly. We are exploring ways to include jitter in the PSF models. The analysis presented in Section 5 was done with a simple nominal-focus library PSF. Even without taking jitter into account in our PSF models, we are still able to make high-precision measurements.

However, if the jitter gets worse, it may be necessary to include jitter in the PSF models we use in high-precision measurements. Although a broadened PSF will not produce the same results as a sharper one, if we use a broadened PSF in the analysis, then we will at least remove the error that comes from PSF mismatch. We explored solving for jitter in our star-fits in Section 4. It would not be hard to fold this into the PSF models. Alternatively, we could take the jitter distribution from the `_jif` engineering files and fold that directly into the PSF model for a given exposure. We will explore these issues over the next few months as we package the focus-diverse PSF models for release.

Acknowledgements

We thank Linda Dressel, Kailash Sahu, and Matthew Bourque of the WFC3 Branch’s PSF group for many useful discussions on PSFs and jitter.

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