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HST Focus in Year 2000. A Review of the Cycle 9 Focus Monitor Program

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ABSTRACT

After the last HST refocusing in June 2000, an enhanced OTA focus monitor (8829) began running as a cycle 9 observatory-level calibration to supplement the existing WFPC2 focus checks made as part of their standard photometric / decontamination monitor. The test was designed to improve our understanding of both the HST focus state and of the monitoring itself, allowing us to track and predict OTA focus changes, which during the past two years have been less smooth than anticipated. In addition to providing better temporal sampling, 8829 also utilized STIS imaging which helped quantify an apparent systematic between the two SIs. The program's WFPC2 observations were made in two filters and at two chip positions, also to test systematics. None were found. A review of the focus results show that since the June 2000 refocusing, there has been no meaningful trend in the focus state of HST. As an appendix, findings are presented which do not support the hypothetical scenario of an accumulation of observed coma as the result of a failed secondary mirror actuator.

Introduction

HST has exhibited since its deployment a focus trend due to shrinkage of its metering truss. This has required periodic Secondary Mirror (S.M.) moves away from the Primary Mirror (P.M.) to maintain focus. The rate of this trend has decayed roughly like an exponential. However in early 1999 as the rate was approaching zero, the focus observations indicated the behavior had become more discontinuous, displaying jumps and/or resumption of significant rates. Further description of this, along with a general review of OTA focus history and STScI's monitoring techniques can be found in the January 2000 STScI memo *OTA Focus Review & Status Entering SMOV3A (http://www.stsci.edu/instruments/observatory/SMOV3Afocus2.memo.pdf)*

In response to this focus behavior, the SISD and OSG groups designed a cycle 9 calibration proposal, which we may continue with modifications if necessary into cycle 10. This program, 8829, runs once a month, and was timed to take place roughly halfway between WFPC2 decons and their attendant PSF checks, ensuring focus determinations every 2 weeks. Unlike the decon focus check, each 8829 visit obtains data suitable for focus analysis over a large fraction of an orbit, giving us a better estimate of the orbital mean focus, and an important ongoing periodic check of the breathing model's efficacy over time. Seven months of the year, the photometric standard star GRW+70D5824 is observed in WFPC2 PC with both F547M and F555W filters. This is the same target used for the decon associated monitors, providing a sort of control. Alternating filters within the orbit allows us to best isolate those filters' effects on the phase retrieval (P.R.) algorithm. For the remaining five months of the year the target is M35, where parallel STIS images are made along with the PC in order to validate or qualify STIS as a potential independent check to our focus monitoring, and if so to better quantify its focus offset to the PC.

See Appendix B for details of the 8829 observations.

Focus Status

Figure 1: Year 2000 focus measurements.

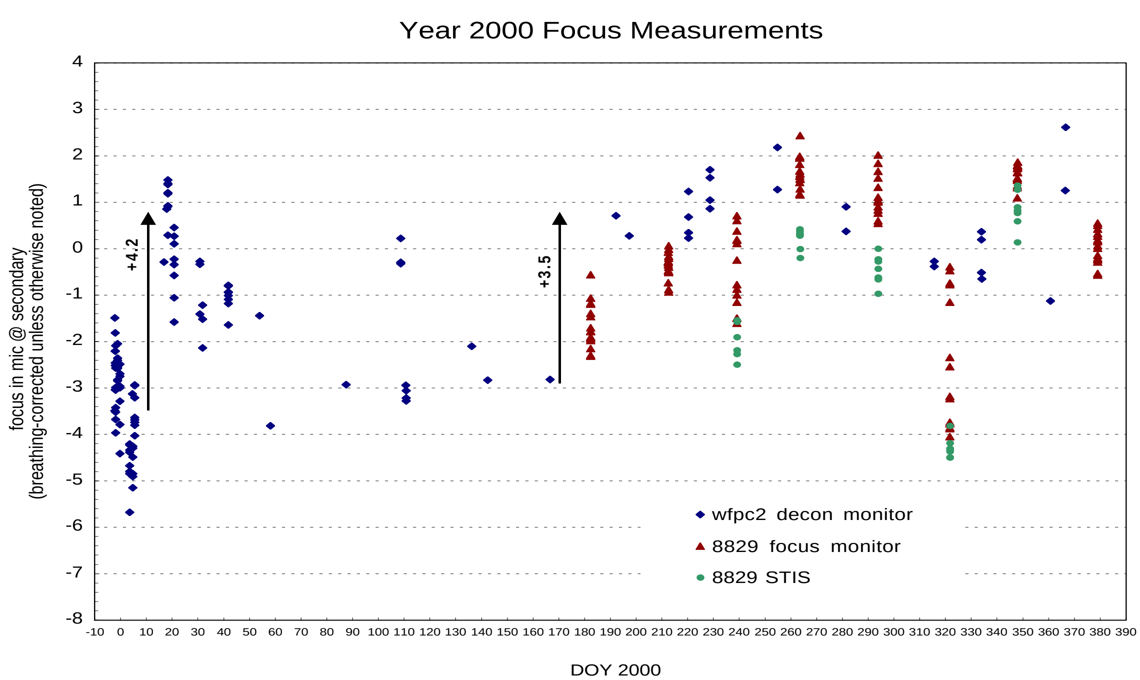
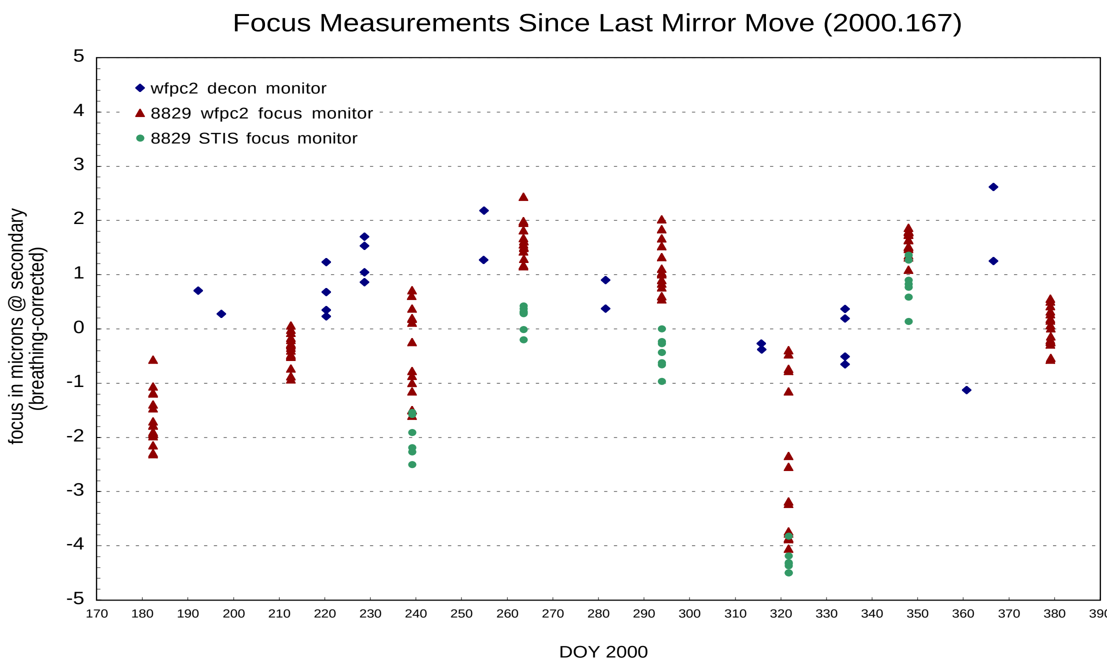


Figure 1 depicts HST focus measurements from just before the SMOV3A mirror move (i.e. focus adjustment) and ends with the January 2001 visit of 8829. Mirror moves are indicated by vertical arrows. Their start point is the estimated focus prior to the move, and their length is the magnitude of the move. The eight monthly visits of 8829 and their distribution between the ongoing decon monitor are clear. As can be seen, during SMOV3A, a focus adjustment was made (2000.009, +4.2µm). This brought HST very close to best PC focus (0 µm). Between days 10 and 160 however, the WFPC2 decon monitor, then the only focus monitoring, described a continuing negative trend bringing the focus to ~ –3µm and outside our nominal tolerance of +/-1.5µm. On day 167, a +3.6µm move was made, and a few days later the 8829 focus monitor began.

Figure 2: Assessment of focus since last mirror move.



The table below gives some statistics for figure 2.

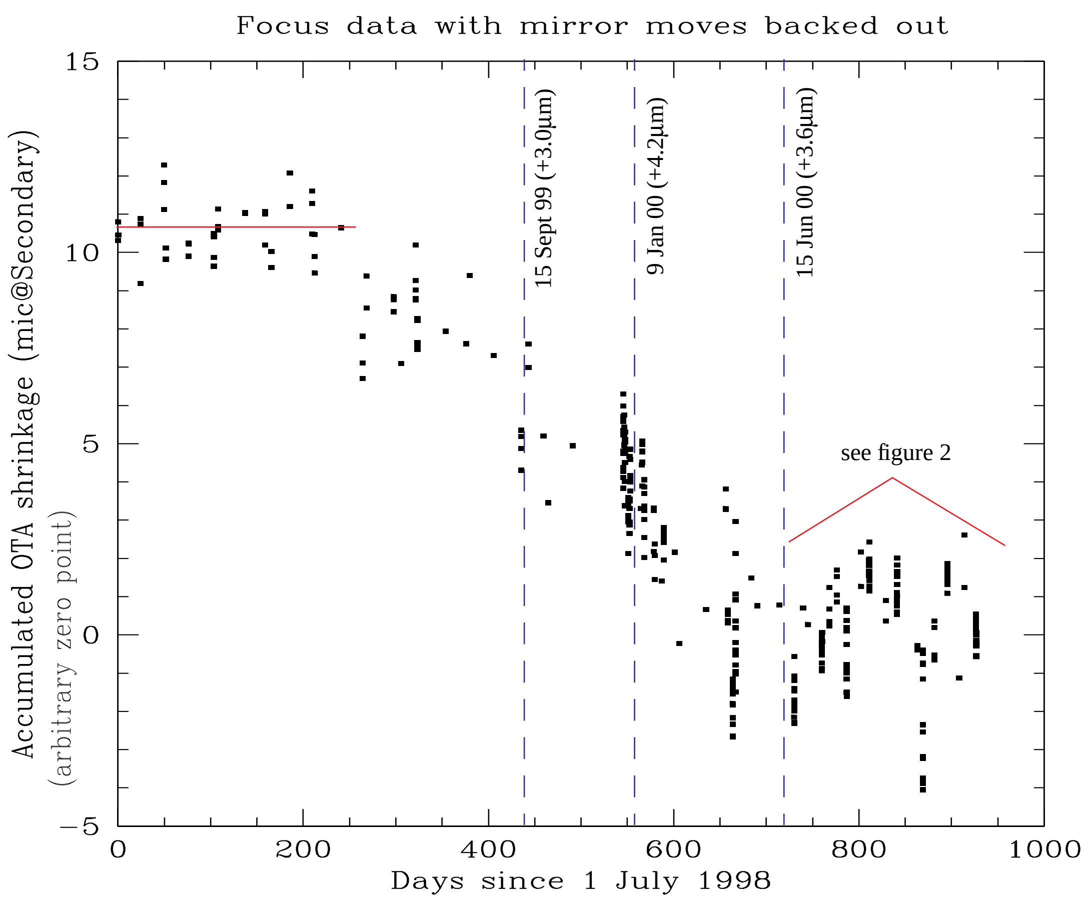
	mean (µm)	slope (µm/month)	scatter (µm,1 σ)
8829 WFPC2	–0.1 (+0.2*)	+0.2 (+0.3*)	1.5 (1.2*)
decon monitor	+0.6	–0.1	0.9
8829 WFPC2 + decon monitor	0.0 (+0.3*)	+0.15 (+0.25*)	1.5 (1.2*)
8829 WFPC2+decon monitor (orbit means)	+0.3	+0.25	1.2

* discarding visit 6, (day 321) which had known extreme breathing that was not fully correctable (see later section on breathing model checks)

Please note that error bars are not represented in these focus plots. There are medium timescale components to the focus behavior that are not well modeled, and placing error estimates on the P.R. data even with breathing corrections is difficult. We have been using a figure of ~ +/–1µm rms measurement error for the P.R. but the uncertainty due to unmodeled breathing at a given time is comparable. The tabulated values show a mean for each subset remarkably near best PC focus (0µm). Scatters are very consistent with what we have seen in past focus monitoring. The slopes are quite shallow and formally positive, so we conclude no statistically significant negative trend in any of the data.

Figure 3 below illustrates the behavior of the monitored PC focus (and by extension the OTA) since July 1998. This plot has the mirror moves added back in to present the continuous long term trend. Evident is the flat portion in the first 250 days, which appeared to be consistent with the decay of the exponential function fit to the data from previous years. After this stable epoch, note the jumps and trend negative for the next 1.5 years, which necessitated three refocusing mirror moves totalling 10.7µm in less than 300 days. After this last refocusing, the current stable epoch shown in detail in figure 2 can be seen, this time in the context of the earlier behavior.

Figure 3: Overall focus trends since 1 July 1998

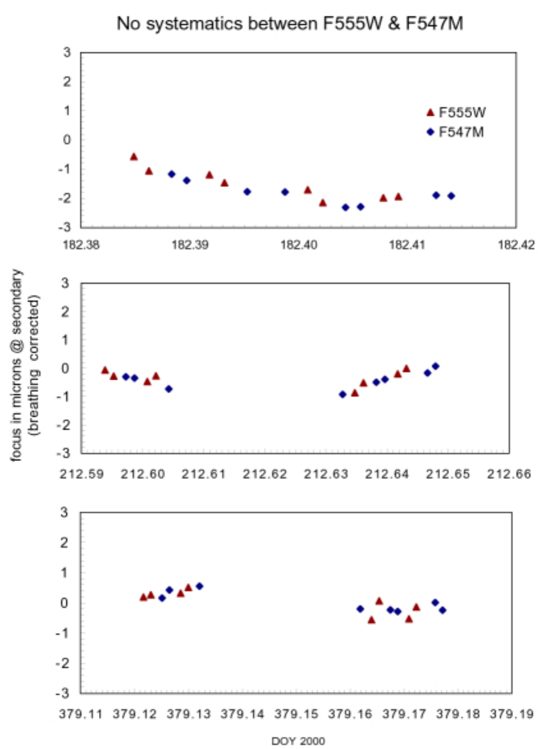


Ultimately, we may expect HST to enter a period of no long term focus trend and remain there. Under this scenario it is imaginable that the calibration time spent focus monitoring could be reduced. However the history makes clear the importance of having the data sampling to react to unexpected changes like that illustrated in figure 3. For now 8829 will continue to run, at least until six months after activation of ACS and establishment of its baseline focus measurements, at which time best approaches to monitoring the HST focus should be revisited.

Checks on Systematics

As mentioned, 8829 was designed to give us information about the monitoring itself, and the validity of various types of focus observations. The brighter stars in 8829's M35 visits required use of WFPC2's narrower F547M filter, necessitating cross-calibration with F555W. Visits to the usual GRW photometric standard star were therefore made by alternating the F555W and F547M filter within the same orbit to discern if bandwidth or other effects from these two filters affect the phase retrieval algorithm's focus result. Figure 4 illustrates no significant effect.

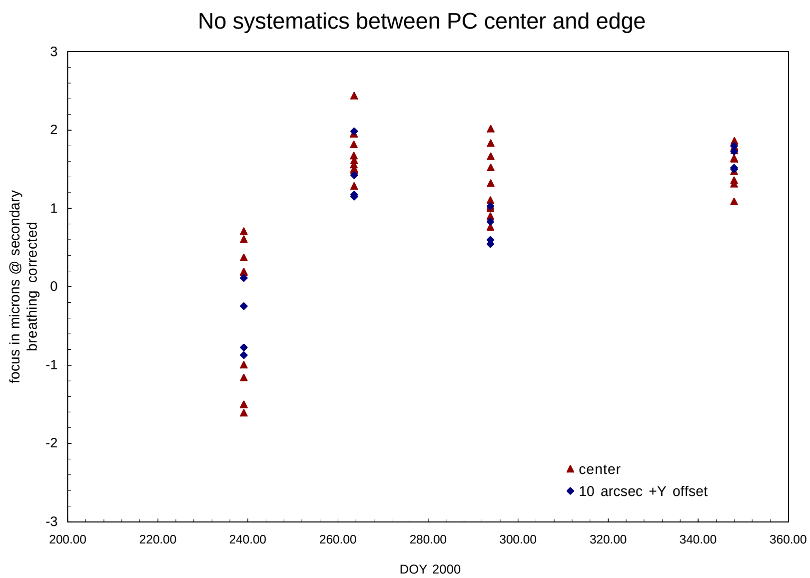
Figure 4: Phase Retrieval of GRW target in two filters



The means of the F555W and F547M sets are practically indistinguishable at –0.6µm and –0.7µm respectively, and they have comparable noise (0.8µm and 0.9µm 1σ rms)

Having interspersed position offsets on the PC chip within an orbit and with the same filter, 8829 also provides a good confirmation that our focus result from phase retrieval is not affected by location of the star on the PC chip. Again, the two sets means are essentially equivalent at +1.0µm and +0.9µm for the centered and offset target. (Figure 5)

Figure 5: F547M filter observations at PC center and with 10" offset.



Visits where STIS images were taken in parallel with WFPC2 allowed us to assess systematics between the focus determinations with the STIS CCD images and WFPC2 PC by minimizing the breathing and time variables. (Figure 6)

While the STIS and WFPC2 data exhibited very similar noise (both ~0.4µm rms average for each orbit) there was a significant and consistent offset between the SIs' means seen in each orbit: –1.54, –1.43, –1.61, –1.85, –0.75. These offsets averaged ~ –1.4µm, an amount which at ~1/2 a typical orbital breathing amplitude is the level of error expected from earlier attempts to set STIS confocal with WFPC2 while the focus was changing due to breathing, and without having had the control that 8829's parallel observations offer. Note that in the STIS CCD imaging modes, this 1.4µm offset is in addition to a 4.3µm offset to the focus at the STIS spectrographic slit plane, where the STIS focus in optimized, and we see no evidence of a focus problem for STIS based on their small-slit throughput monitoring. Therefore, we conclude that at STIS best spectroscopic focus, the STIS CCD images are defocused by the equivalent of 5.7µm (4.3+1.4) of S.M. despace or 1/19 wave RMS of defocus @ 6328Å relative to the WFPC2 PC.

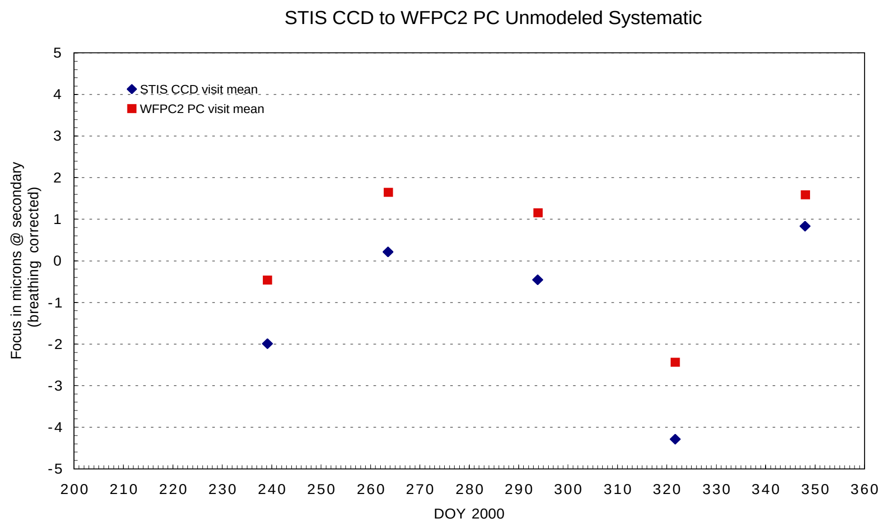
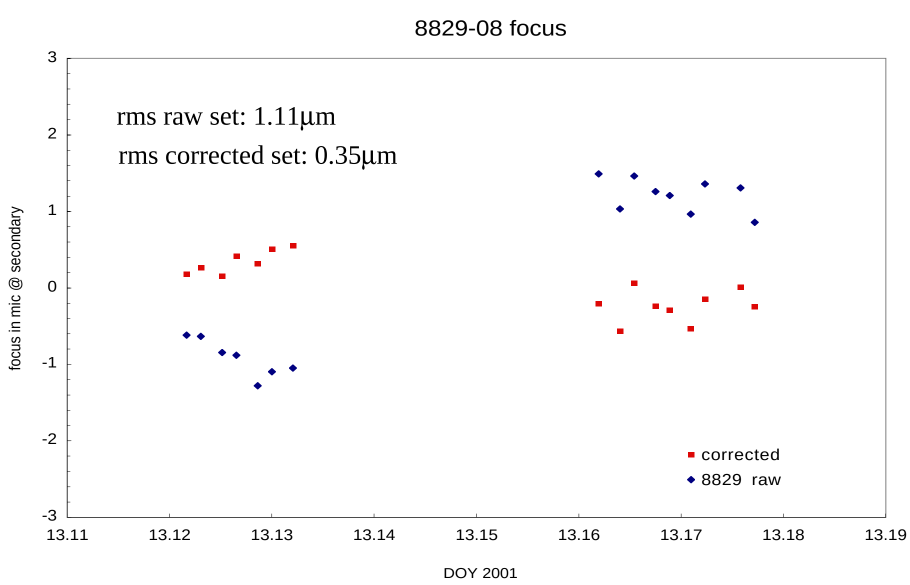


Figure 6: Offset between orbit means of STIS CCD and WFPC2 PC focus results.

Breathing Model Checks

There has been strong evidence that STScI's full temperature breathing model, (*http://www.stsci.edu /instruments/observatory/focus/sesdrep.pdf*) performs better at reducing scatter within an orbit than it does over longer timescales. By obtaining data continuously over an orbit, 8829 has provided good examples of the breathing corrections at work over an orbit, regularly reducing residuals from >1µm to 0.3-0.4µm rms. Figure 7 illustrates the model's effect in one example orbit (8829, visit 8).

Figure 7: Breathing model's typical reduction of scatter within an orbit.



However, as indicated in table 1, even with the breathing corrections, the scatter in the 2000 data using only the *means* of each orbit is >1µm, implying that there is still an appreciable amount of unmodeled behavior on timescales of days to weeks and it is this uncertainty that complicates predicting the baseline OTA focus state. Considering all points since 8829 began (figure 2) the overall scatter on the raw data is 2.2µm while the corrected set yields 1.6µm, a significant reduction, but not low enough to definitively determine the baseline OTA focus state from a set of measurements more infrequent or less in number than what we currently utilize given the behavior in figure 3.

Furthermore, during larger than normal breathing excursions, which can depress the means of many contiguous orbits and are believed to be due to HST attitude histories producing abnormal temperatures, the breathing model tends to underestimate the extent of the focus excursions. We have seen examples of this in the past, and most recently, visit 6 of 8829 highlighted this phenomenon, containing images measured as far out of focus as –7.7µm. Even with the breathing correction, this visit was a statistical outlier with its corrected mean of –2.4µm being 2σ from the ~0µm +/–1.2µm value derived from the other visits' means (table 1). As expected, it also exhibited a much higher scatter about its corrected mean than the other visits (1.4µm vs. 0.3-0.4µm).

Figure 8: Outlying 8829 visit 6 PC data, showing inadequate modeling

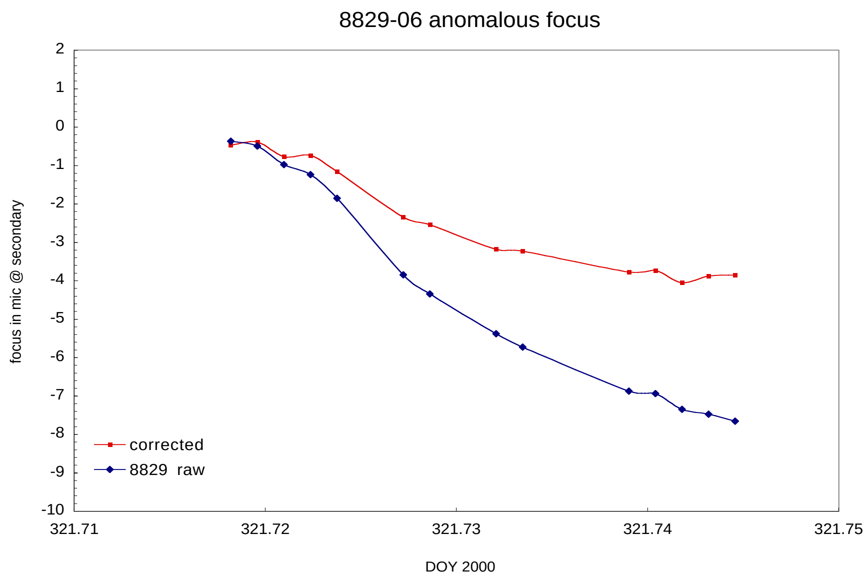


Figure 9: PC star image at ~ -8µm of OTA defocus

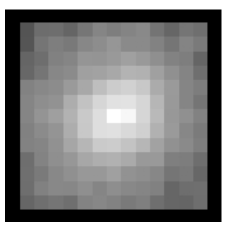
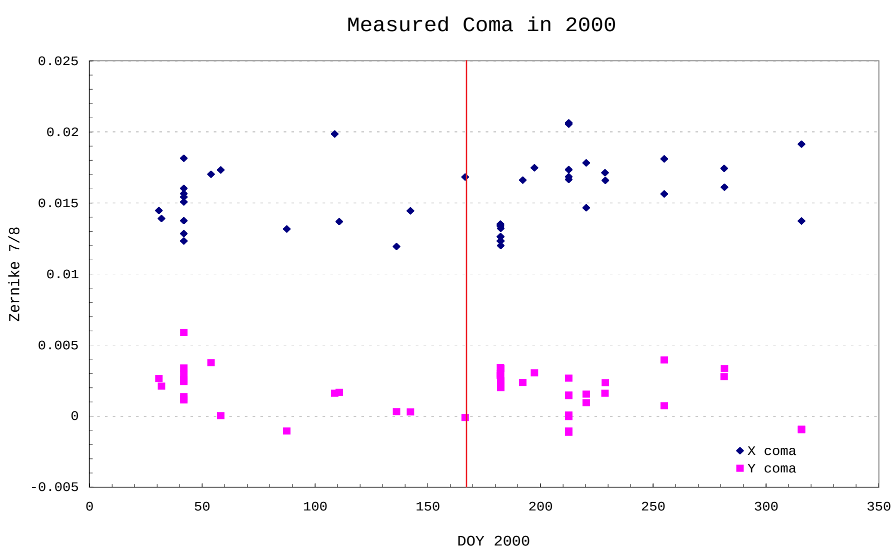


Figure 9 shows a point spread function (PSF) from visit 6. Noticeable should be the elongation of the PSF from upper right to lower left. This is due to astigmatism in the WFPC2 PC optics, which switches axes 90º as the defocused OTA image passes through best focus, and becomes more pronounced with defocus. This is a unique advantage of the WFPC2 for focus monitoring via phase retrieval since the SI-induced distortion of the PSF with OTA focus aids in the iterative fitting that the algorithm performs and breaks the symmetry that can exist on either side of focus.

Appendix A: Evidence for large coma due to an increasingly tilting S.M.?

Shortly after Serving Mission 3A, HST Project asked STScI and Raytheon to investigate the effect that a hypothetical stuck S.M. actuator would have on phase retrieval focus measurements as the S.M. was commanded in defocus. A Raytheon memo (Abramowicz-Reed, 2000) described the primary effects would be a tilt (which we cannot measure with phase retrieval), and X & Y coma (Zernikes 7 & 8). Due to limitations comparing historic phase retrieval coma results, as well as incompletely archived coma data, long-term trending of fitted coma values was not possible. A more controlled analysis can however be performed on our 2000 data before and after the day 167 mirror move of +3.6μm, (figure 10). For a +3.6μm S.M. move, Raytheon's simulations predict a total coma Δ of 0.01. This is the resultant of the X and Y coma components. The direction of this vector would depend on which actuator failed. Using only consistently analyzed F555W data from before and after the mirror move, we observe a total coma shift of 0.001 +/–0.004, a factor of 10 less than predicted. Assuming a normal distribution, Z=(0.01–0.001)/(0.004/sqrt(n)). n = #of points = 46 so Z=15, indicating it is extremely unlikely that our data is consistent with a 0.01 change in coma as predicted by the Raytheon simulation.

Figure 10: Measured X and Y comas bracketing mirror move.



According to the stuck actuator prediction, our past three mirror moves alone should have produced a Δ coma of 0.035, a value which is much greater than coma variations noted when comparing current numbers to data as far back as 1996.

Because of HST's spherically aberrated wavefront, the FGSs are more sensitive to tilts and decenters of the S.M. than the SIs. An independent check for such inadvertent movements using FGS data was reported in a memo (Nelan 1999), which concludes "At the level of FGS1r sensitivity, there has been no measurable change in the tilt and/or decenter of the OTA's secondary mirror over this interval of time [1999.001-1999.258]." This period bracketed a 3μm mirror move.

Appendix B: 8829 Observations

During the WFPC2-only visits, the spectrophotometric standard white dwarf GRW+70D5824 (Vmag. 12.8) is observed at the PC1 reference 16 times in one orbit. Alternating four times between two 3.5 second exposures with F555W and two 8.0 second exposures with F547M. These exposures produced S/N ~400 (gain=15).

For the visits which used STIS in parallel, WFPC2 observed an 11.9 mag M35 cluster member in the following sequence: five 3 second exposures in F547M at the PC1 reference, four exposures at a 10.4" offset, then five more back at the reference. These exposures give similar S/N as with the GRW target, and result in central pixels at about 70% saturation (gain=15).

The STIS exposures of a 9.7 mag M35 star are taken in parallel and are made at the CCD reference. Four 30 second exposures are made in the F28X50 OII filter followed by three 60 second exposures with the OIII filter, again producing values ~70% saturation. The OIII and the OII filtered observations were found to give equally reliable phase retrieval results and future incarnations of the focus monitoring could utilize only the OII filter, which due to its wider bandpass and subsequent shorter exposure time, can produce more data points within an orbit.

In general, when considering images for use by the phase retrieval code, care must be taken to avoid overexposure (since the phase retrieval algorithm is intolerant of saturated pixels in the PSF), while at the same time balancing the fact that the phase retrieval code performs better as the PSF becomes more monochromatic (narrower filter), against the fact that it performs worse as the exposure time becomes longer, due to orbital focus changes smearing the PSF.

References

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