

HST Temporal Optical Behavior & Current Focus Status

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ABSTRACT

HST focus has been monitored throughout the Observatory's life. The preferred technique is a phase retrieval method which solves for certain Zernike coefficients, usually focus, coma and astigmatism, from model fits to the nearly in-focus PSFs. Here, we discuss what data from the ongoing monitoring strategies and special observations tell us about modes and timescales observed in HST optical variations, and suggest examining the current scientific need for PSF characterization. As the primary purpose for this monitoring is to support accurate focus maintenance, we also present a picture of the current focus state of the Observatory.

Introduction

It has been known since early in the Mission that the focal length of HST varies on both orbital and longer time scales. These changes have generally been attributed to a physical motion of the secondary mirror (SM) resulting from variations in the metering truss structure that supports it. Successive improvements in the complement of instruments aboard HST have generally increased the sensitivity of image quality to focus, while simultaneously improving our ability to measure the focus and infer the SM position through PSF properties. Recent observations with ACS/HRC have enhanced our ability to measure additional image aberrations, such as coma and astigmatism; like defocus, these aberrations vary over the HST orbit, suggesting the possibility of a more complex motion of the SM. This is an area of growing interest because of the sensitivity of recent science investigations to the details of the PSF, which in turn is affected by the changes in image aberrations.

Despite several attempts (e.g., Hershey 1997), the development of a successful predictive model of the focus variations of HST has proven elusive thus far. A number of drivers are likely present at any given time, and their complex relationship may ultimately be unpredictable (Ma-

rochnick et al 2000). However, monthly monitoring data, combined with an improved understanding of typical focus variations, allow us to estimate the expected value and range of focus positions over a period of time approaching a few months. The regular monitoring of coma and astigmatism that we have recently begun is expected to yield a similar understanding of the origin of these aberrations and a better characterization of their orbital and long-term variations.

Part 1 of this report describes the current state of our understanding the aberration variations (including focus) over various timescales, while Part 2 details the overall focus state since the last re-focusing was performed in late December 2004.

Part 1. Timescales & Mechanisms for Changes in HST Focus and Aberrations

1. Orbital Effect on Focus (“breathing”)

A smooth change in measured focus locked to the HST orbital period was noticed very early in the Mission. Bely et al (1993) established a relationship between the oscillating focus and four temperatures obtained from sensors at the HST’s aft light shield, just fore of the secondary mirror spider supports. The relationship is:

$$(1) \quad SM = 0.7(LS - MLS) + K$$

where:

SM is the secondary mirror despace in microns,

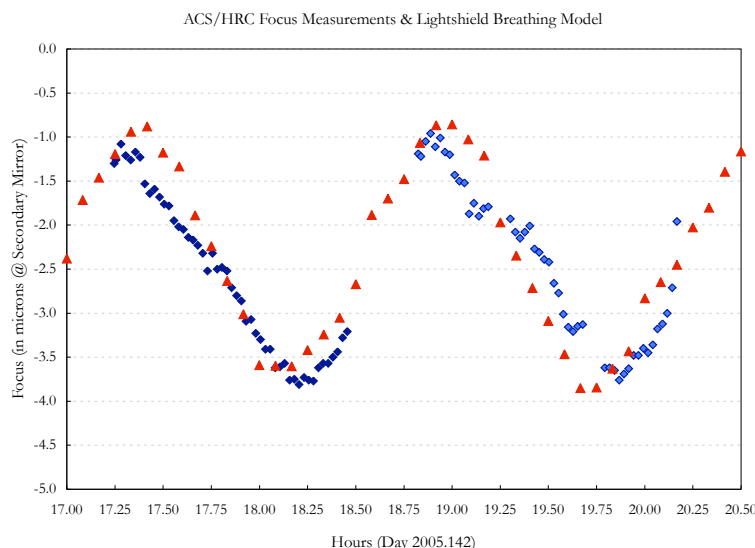
LS is the instantaneous mean of the four light shield temperature sensors in degrees,

MLS is the mean of LS over the previous orbit (previous 95 minutes)

K is a zero point offset

Though this relationship was determined with limited data from the Faint Object Camera, it has remained useful and largely valid for modeling focus change as a function of orbital phase. The factor which scales the amplitude was empirically determined from the FOC data, but in fact can be seen to still fit remarkably well recent data obtained 12 years later (May 2005) with a different instrument (ACS/HRC, see Figure 1).

Figure 1: Focus values¹ determined from phase retrieval analysis of a point source in HRC over two full CVZ orbits (blue). Overplotted in red are the modeled focus values using equation 1.



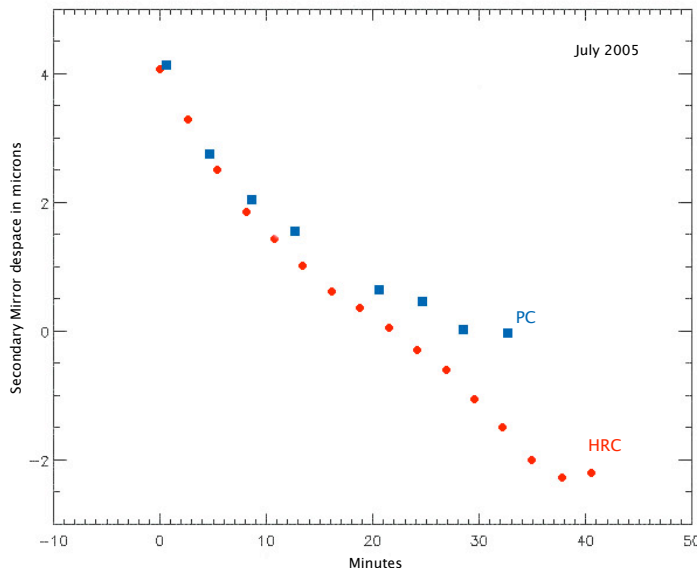
¹ Throughout this report, unless otherwise stated, measured focus, coma, and astigmatism values are determined from a Phase Retrieval routine developed by John Krist (Krist & Burrows 1995) which iteratively solves for Zernike coefficients by fitting a stellar image. We normally express the Zernike coefficients in microns rms wavefront error, however, focus (Z4) is converted to microns of HST Secondary Mirror (SM) despace with the zero point being best WFPC2/PC focus, and positive values indicating increased distance between the Primary & Secondary Mirrors. This is a convenient convention when assessing focus adjustments. See Appendix A1 for further details.

The model offset, K , was adjusted to fit the above data. The variability of K reflects the fact that the means of orbital variations trend and behave on their own timescales, complicating focus modeling. This is discussed in following sections.

The fact that HRC and FOC seem to be equally sensitive to the light shield temperature variations implies that the degradation of HST in the environment of space has not resulted in other inputs that significantly affect orbital focus changes. However, despite the good agreement in this case, the scale factor of 0.7 has been observed to vary with observing conditions and from SI-to-SI. Such a case was presented for NICMOS by Suchkov & Hershey (1998), and more recent focus observations acquired with HRC and PC in parallel also suggest SI-to-SI variations in some but not all cases (Figure 2). We point out that ACS replaced the FOC in the Axial SI Position 3 in the HST Aft Shroud, and their very similar breathing amplitudes may relate to this commonality.

It would be valuable to obtain data enabling determination of an accurate orbital scale factor for focus for ACS/WFC, which is the detector used in many studies involving weak lensing and/or the morphologies of barely resolved objects (e.g. COSMOS, GOODS, GEMS). Understanding also the effects of coma and astigmatism in such programs is perhaps more valuable, and is discussed in the next section.

Figure 2: Focus as measured in PC and HRC over a partial orbit, showing variations in breathing amplitude.



Science currently expected to be performed with COS and WFC3 will most likely be sensitive to a varying PSF. The impact of PSF variations could be estimated and assessed in advance of Servicing Mission 4. In the time prior to Servicing Mission 1, the dilated, spherically aberrated PSF, combined with a number of small apertures, made throughput quite sensitive to orbital “breathing”. In the current epoch, observing programs that depend sensitively on a stable or well-

modeled PSF, are drivers for a better understanding of the sources and timescales of observed PSF variations. Suchkov and Casertano (1997) showed that the SM despace variations of a few microns typical of breathing alter photometry for the different WFPC2 cameras by as much as 10% for a photometric aperture of radius 1 pixel, and a few percent for a common aperture of radius 2 pixels. These results are notably worse than the general accuracy goal of 1% photometry for HST. Gilliland et al (2000) discussed actively tracking PSF changes in time and using the knowledge of these changes in one's data analysis. Accounting for PSF changes was critical to the science goals of week-long observing campaigns of 47 Tucana (PI: Gilliland, proposals 8267 & 9750) aimed at detecting extrasolar planet transits with photometric precisions near the theoretical limit (0.3% WFPC2, 0.2% ACS). Addressing the rapidly changing PSF for these crowded-field photometry programs provided the greatest challenges in terms of software development and execution time.

2. Orbital Effect on Coma and Astigmatism

The Bely breathing model expresses the strong correlation between orbital focus swings and differences in the temperatures monitored near the SM support structure. This is broadly interpreted as the result of dimensional changes of the graphite epoxy metering truss comprising the HST Optical Telescope Assembly (OTA). It would seem unlikely that such thermally driven movements of the truss would induce a pure despace of the SM. Tips, tilts, and decenters of the SM, coupled with despace variations, are also considered likely results of thermally-driven motions of the OTA. We would then expect changes in aberrations like coma and astigmatism induced from such motion. However, before the installation of the ACS/HRC, our ability to measure aberrations other than focus was limited. With the ACS/HRC, we have a critically sampled PSF at wavelengths appropriate for phase retrieval. It is also well off-axis, making it sensitive to optical misalignments.

In May 2005, as part of an on-orbit test to understand an operational pointing anomaly, we obtained, along with the Z4 values shown in Figure 1, Zernike coefficients 5 through 8, corresponding to the two components each of coma and astigmatism. The data are quite clean and show a very clear orbital pattern (Figures 3 & 4).

Figure 3: X-Coma (left) and Y-Coma (right) measured at HRC over two CVZ orbits. The X-axis represents time, while the Y-axis is in microns of rms wavefront error.

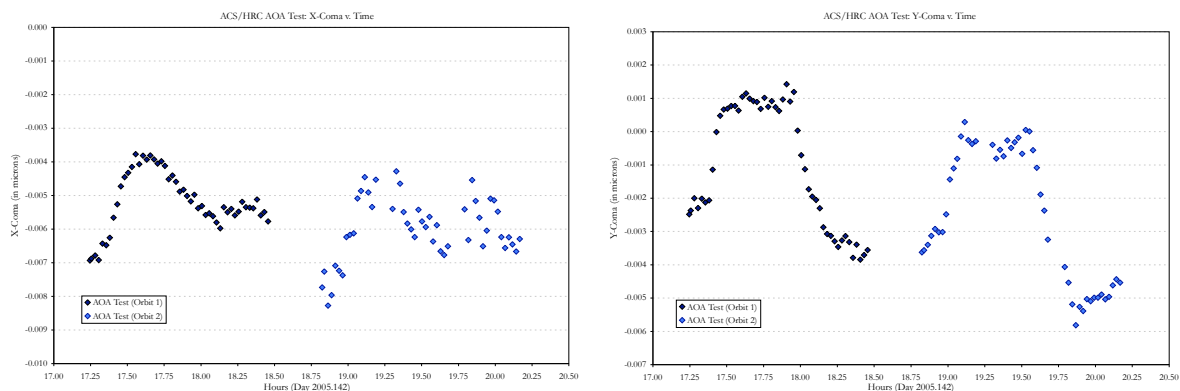
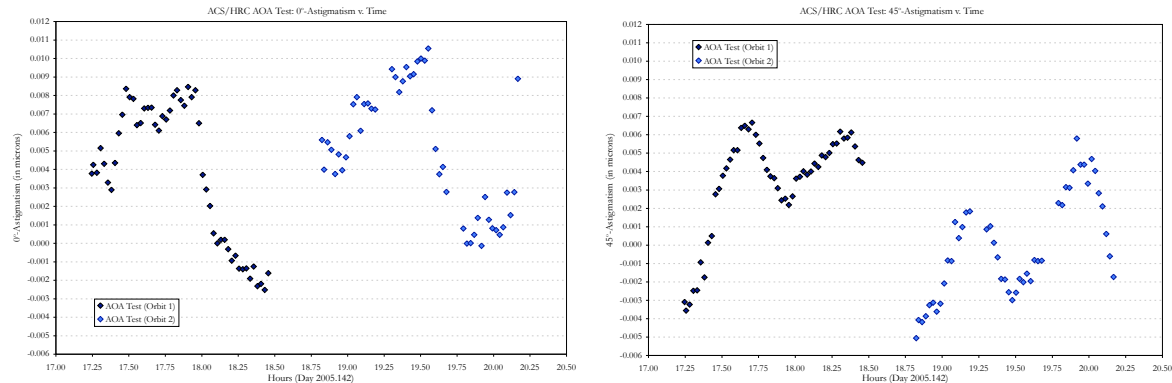


Figure 4: 0°-Astigmatism (left) and 45°-Astigmatism (right) measured at HRC over two CVZ orbits. The X-axis represents time, while the Y-axis is in microns of rms wavefront error.



The y-axes units are microns of rms error at the wavefront, so peak-to-peak variations are in the range of $\lambda/100$ in for coma and $\lambda/50$ for astigmatism at 550 nm.

Beginning in Cycle 14, we have enhanced the standard Focus Monitoring calibration program to include seven visits to obtain ACS/HRC data with high temporal sampling similar to the data shown in Figures 3 and 4 (Prop. Cal/OTA 10752). These data will be used to further understand and characterize orbital effects on the PSF. In addition, the aberrations, when fed through an optical simulation of the HST OTA+HRC, can be used to determine the tilts and decenters of the SM and other optical elements required to produce the observed aberrations; doing so can improve our knowledge of focal image shifts due to optical misalignments and any possible role in HST operations. For example, in the simplified assumption that the observed aberrations are induced entirely by the OTA, then initial analysis of the existing data indicates SM motions of $\sim 50\mu\text{m}$ in tilt and decenter would be required to produce the aberrations measured, large enough to be physically implausible. This suggests mechanisms other than the OTA are at work. Other interpretations should also be investigated.

3. Medium-Short-Term Behavior (“wandering”)

In the orbital breathing model, the uncertainty in the zero point offset K results from the fact that the orbital mean focus can trend over timescales of hours to days by amounts comparable (usually within factor 2) to the orbital variations. When traced back to the SM, values of order 5 or 10 microns (and beyond) of SM despace resulting from this “wandering” results in a visually noticeable amount of defocus in the imaging SIs. This depression of focus was first noted early in the Mission during HST observations of Mars at opposition, and was analyzed by Miebach (1995). It was found to be the result of an extreme sun angle (angle between the sun and the HST +V1 axis), which had HST pointing within a few degrees of the anti-sun direction (180°). As the HST sun angle moves from a nominal 90° toward 180° , the temperatures at the metering truss and light shield drop, creating a negative focus state. Furthermore, when the sun angle increases beyond $\sim 170^\circ$, HST’s larger diameter Equipment Section shadows the Forward Shell containing

the metering truss, causing an additional and pronounced cooling of the truss. In this state, temperatures monitored for breathing can reach -40C (from a nominal -25C +/-5C). While near-anti-sun pointings are not restricted, their potential impact is now known. The wandering of focus over a number of orbits, however, is a function of not only sun angle but other factors affecting heating loads on the spacecraft.

In the late 1990s, Hershey produced two models which attempted to describe both the focus wandering and breathing in a unified manner in order to give the true focus state of HST as a function of time (Hershey 1997). The first model was descriptive and derived from empirical fits of observed focus to linear combinations of functions involving a large number of temperature readings throughout the spacecraft (Hershey “full-temperature” model). The second was predictive and gave focus state as a function of analogous combinations of various vehicle attitude parameters, which could be obtained even from a mission schedule for a future observation (Hershey “attitude-based” model).

Due to the difficulties in obtaining accurate and meaningfully-sampled focus data, and the limited priority of increasing the dedicated calibration time for such observations, the models were never sufficiently constrained or developed. Additionally, they relied on a predictable function for the long-term secular behavior (discussed in Section 4). This smooth, long-term trend broke down in the recent era, producing yet another zero point problem to an otherwise promising model. The present HST configuration of SIs without STIS and its small apertures has arguably reduced the sensitivities of primary science programs to focus, while shifting concerns toward the types of science described in Section 1 and the understanding of the other aberrations.

While the Hershey models were being developed and tested, they usually - but not always - performed well on the limited amount of data available. However, the attitude-based model was especially significant for illustrating some of the operational drivers and physical scenarios that affect the HST dynamical response to heating.

Figure 5: Medium-short-term focus wandering. The top curve illustrates these excursions of HST focus which occur over scales of hours to days and can be large compared with the orbital swings (high frequency variations). Also plotted are the input parameters upon which the attitude-based focus model relies. Correlations with HST attitude history are apparent.

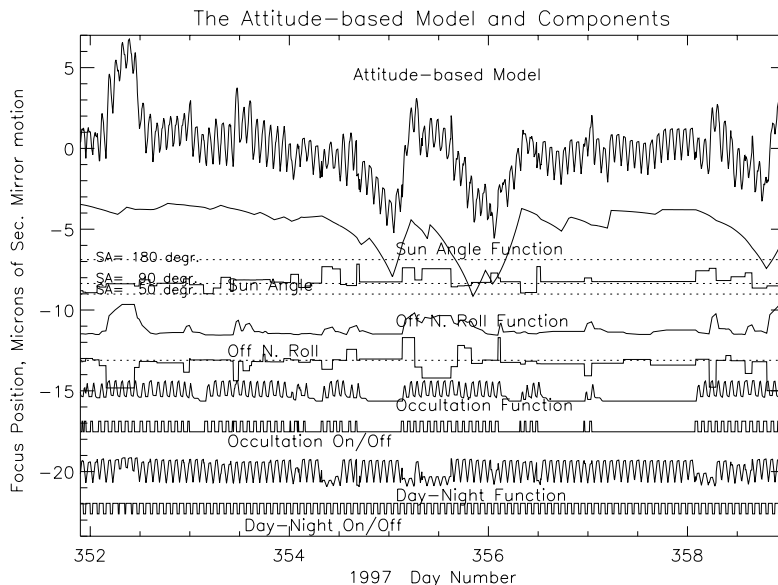
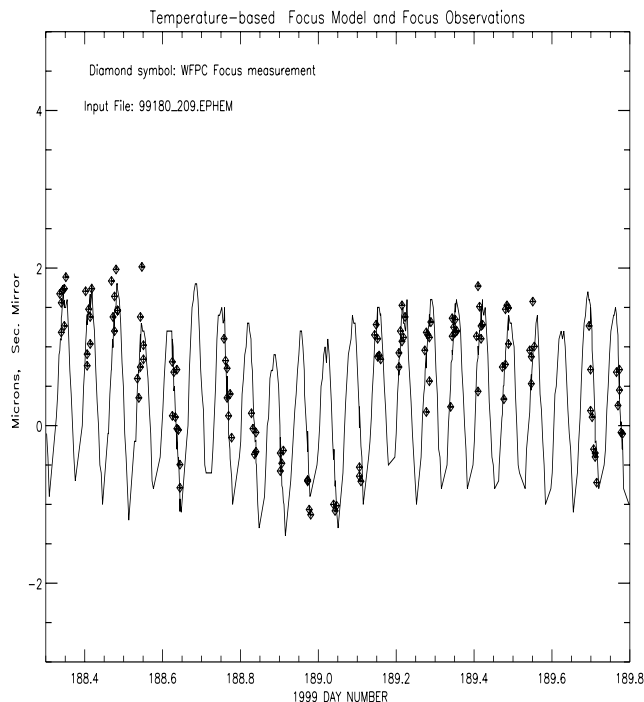


Figure 6: Focus measurements performed on science targets during July 1999 GO observations were well-fit by the Hershey full-temperature model which is overplotted. Comparison gives rms difference of 0.5 microns. Excursions of the orbital mean over the 1.5 days plotted was in this case less than the orbital range.



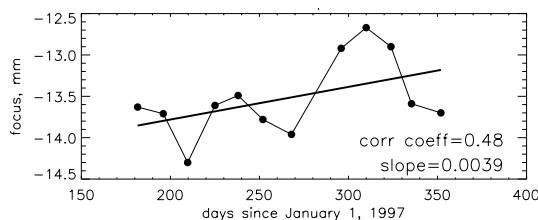
The discussions in this section have dealt with focus over timescales greater than an orbit and less than a few weeks. Aberrations like coma and astigmatism may display wandering similar to the focus, due in part at least to the same dynamics which induce despace in the secondary mirror also producing small tilts and decenters. Aberration data have in the past been more scarce than focus (only accurately measurable with ACS/HRC) and less details are known about the behavior in this regime, although the determination and monitoring of aberration values have been given more attention in Cycle 14.

4. Medium-Long-Term Behavior (seasonal & precessional)

Adding to the orbital swings and the wandering over multiple orbits, some instruments have seen periodicities correlated to HST orbital precession as well as the earth/sun orbit. These are observed to affect both focus and at least some of the aberrations.

The pole of the HST orbit precesses with a synodic period of about 56 days. HST's mean aspect with respect to the sun varies as a result of this cycle. A period consistent with this mechanism was found in data acquired during intensive optical monitoring of NICMOS in 1997 (Suchkov 1998). This effect measured at NICMOS has an amplitude of $\sim\pm 5\ \mu\text{m}$, which is comparable to, but somewhat larger than, typical orbital variations.

Figure 7: From Suchkov 1998. Representative focus measurements obtained with NICMOS. Data sampling was not sufficient to yield reliable frequency estimates, but all such data was consistent with the HST synodic precession period of 56 days. Note focus is expressed in mm of NICMOS PAM. (1 mm PAM = $\sim 8.3\ \mu\text{m}$ at the SM for NIC3)



These data also showed significant correlation with temperatures measured at NICMOS, indicating that thermal variations and sensitivities local to the SI may play an important role. Supporting this is the fact Hershey's temperature and attitude models predicted this period with much less amplitude than observed at NICMOS ($\pm 1\ \mu\text{m}$), and this smaller amplitude was found to best reduce residuals in WFPC2 focus data. It seems that both the HST OTA and at least some of the SIs are sensitive to this effect.

Though this period is worth noting here, the effect appears to be smaller for the other SIs, and not unsurprising based on our general expectations of temperatures' effects on focus. Subsequent routine monitoring using other SIs has not featured sampling rates sufficiently frequent to further explore this timescale.

On still longer timescales, eccentricity in the earth orbit produces a variation in solar intensity with a half-amplitude of 3%. We also know that an important heat input driving HST temperatures is IR radiation from the earth encountered during occultations. These effects could

conceivably produce an annual period, and in fact we do see periods in optical monitoring data suggestive of annual fluctuations in HST temperatures.

Figure 8: Focus monitoring data obtained with HRC over the SI life (3+ years to date). Points are the means of measurements from individual visits executed roughly monthly. The curve is the 30 day moving average of those points. The plot is folded to 1 year.

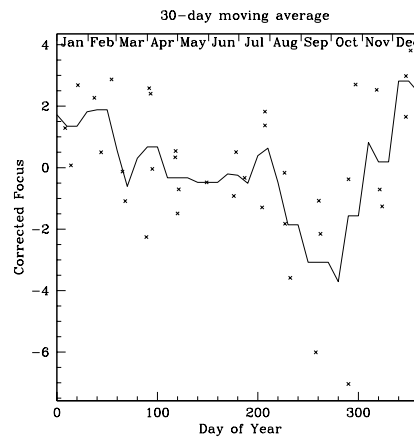
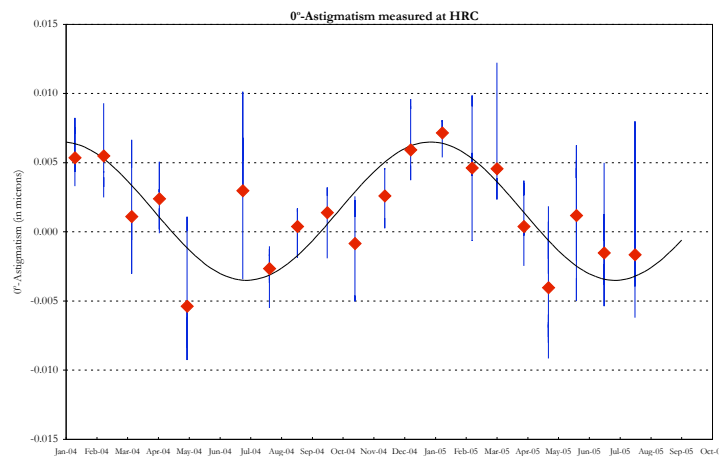


Figure 9: x-Astigmatism, measured from optical monitoring data from the HRC. Points are the mean of measurements from individual visits executed roughly monthly. Blue bars represent the peak to peak spread of values obtained over the orbit (see Figures 3 & 4). Plot spans ~1.7 years starting Jan '04.



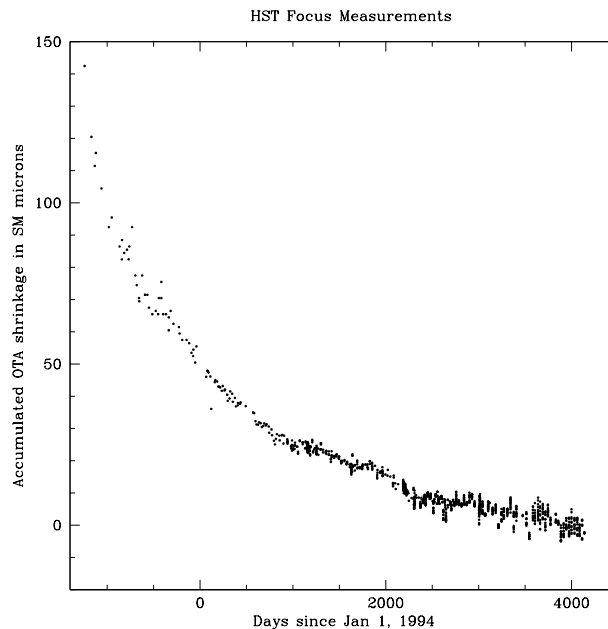
As with the 56 day precessional period, it is unclear the degree to which thermally induced motions in the OTA or the SI contribute. As noted earlier, preliminary analysis of the observed astigmatism ranges indicate an amount of SM motion too large for the likely primary mechanism to be the OTA. Work is ongoing.

4. Long-Term Focus Behavior (desorption)

The longest timescale in the HST optical system is a secular trend toward negative focus values. Since HST deployment in April 1990, the Secondary and Primary Mirrors have moved toward each other a total of $\sim 150\ \mu\text{m}$, resulting in at least 21 SM despace adjustments to maintain “best” HST focus (based on the requirements driven by the SIs extant in the various epochs). Early in the Mission (pre-refurbishment mission), refocusing were performed frequently (2 to 3 times a year) and were typically of much larger magnitudes than today’s. It was common to command 20 microns of SM despace, and focus monitoring techniques even included measuring the distance between the three PM support-pad shadows in the highly spherically aberrated PSF. (Hasan & Baxter 1993)

The basic long-term behavior during roughly the first half the Mission appeared to be exponential in nature, a function both predictable and consistent with the generally believed model of moisture in HST’s graphite epoxy metering truss (Carter 1985) being forced out (“desorbed”) by space vacuum. Such desorption would result in a shrinkage of the truss (and hence the trending of the SM toward the PM) with a rate proportional to the amount of absorbed material remaining (Figure 10).

Figure 10: Shrinkage of the HST metering truss since deployment, expressed in accumulated microns of negative despace of the SM. Trend was well modeled with an exponential until late 1997 (> day 1300) when the shrinkage became more unpredictable.



The specific exponential function(s) were determined in the past by Hasan (1993) and redefined later, using data through 1997, by Hershey (1997). This predictable overall function and the sawtooth pattern which represented the periodic refocusing discontinuities (Figure 11) formed the baseline focus as a function of time, on top of which Hershey’s models expressed variations.

Figure 11: Focus monitoring with WFPC2/PC and the fit function used in the past as a zero point for the detailed focus modeling described in Section 3. These models are no longer in regular use in part as a result of the continuing deviation of OTA shrinkage from a smooth function.

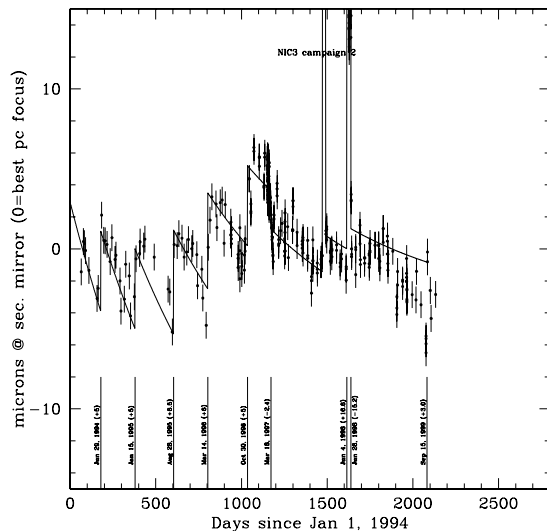
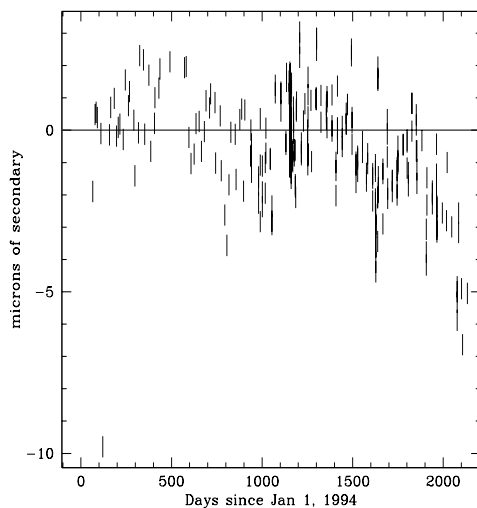
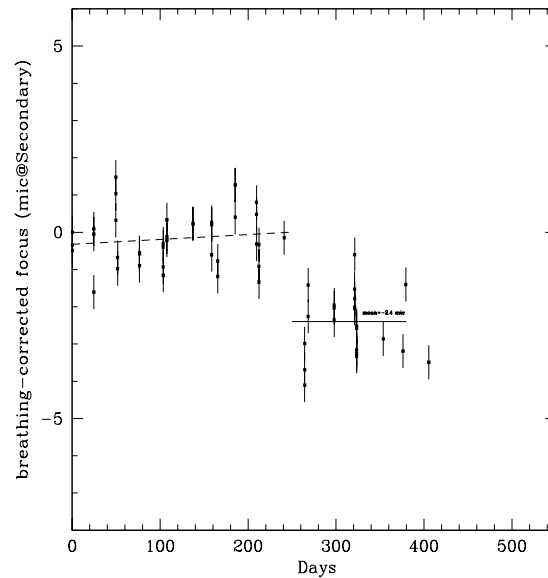


Figure 12: From Lallo et al (2000). Deviations from the desorption exponential. Points represent measured focus values minus the exponential function which was abandoned by 2000.



In this latest epoch of long term focus behavior (~2000-present), we see primarily negative trends of much flatter slope than in the past, combining with seasonal and other variations discussed above. In the past four years, there has only been need for 2 refocusing of the Observatory, however careful monitoring continues to be required since the focus state observed in this “low-desorption” phase exhibits varying rates and discontinuities such as the March 1999 event seen in Figure 13.

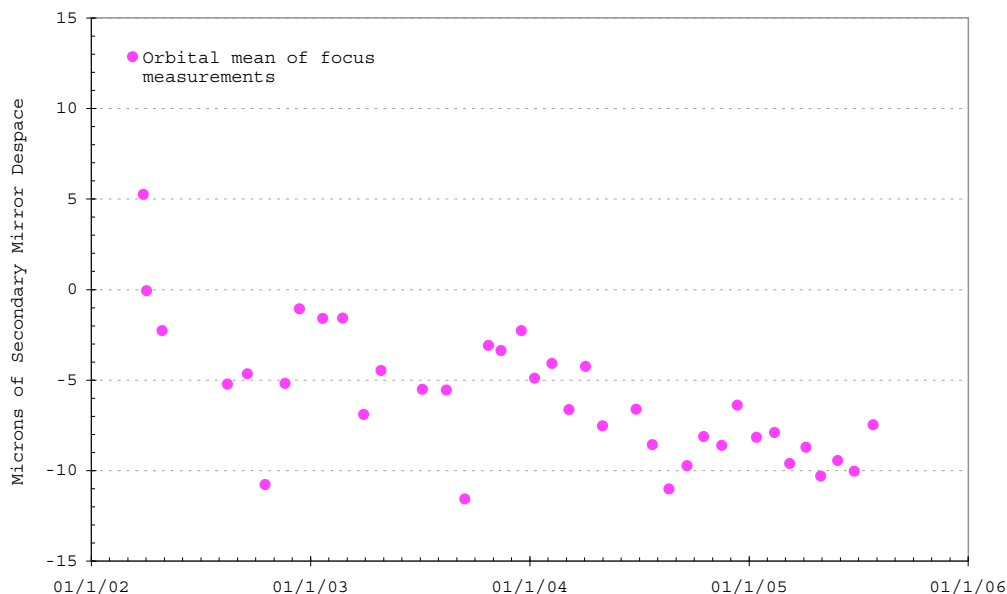
Figure 13: Discontinuities are seen in present era when desorption is less dominant.

These events might be interpreted as a brittle, desiccated metering truss settling into a more compact state in small creaks or snaps, but in the absence of materials expertise or models, this is purely speculation. With this mechanism in mind, however, it is important to note that coma and astigmatism, accurately measured at HRC, have not been observed to trend during the life of the SI, from 2002 to present. The flat baseline seen in Figure 9 is one example. The other Zernike coefficients characterizing coma and astigmatism likewise show long-term stability. Stability of coma measured with PC was established using earlier data over a shorter baseline (Lallo et al 2001).

We interpret these findings as an important indicator that as the truss settles, it is doing so in a way that is symmetric about its longitudinal (V1) axis. It is not accumulating a bend or other deformation, as this would induce a trend in the measured aberrations by affecting SM tilts or decenters, in a way analogous to the symmetric shrinking affecting focus via SM despace.

To illustrate the long-term trend for the past few years, focus measurements obtained monthly with HRC were reduced to a mean for each visit, and corrected for refocusing moves of the SM in order to show the continuous behavior (Figure 14).

Figure 14: HRC focus data with the last two SM moves subtracted shows continuing migration of the SM toward the PM, but at a rate much lower than in the past. Seasonal variations, shorter-term wandering, and differing targets and visit geometries contribute to other patterns and differences in scatter.



An attempt has been made in the first part of this ISR to summarize the timescales and mechanisms at work which affect HST’s effective focal length and optical alignment. HST’s dynamical responses to thermal inputs are numerous and not understood in great detail. They remain one of the most complex and subtle mysteries of the Observatory. Fortunately, solid thoughtful design and mechanical engineering that was state of the art 25 years ago has kept most of these effects manageable, whether considered from the perspective of spacecraft operations or scientific data quality, despite HST nearing two decades in space. We have however pointed out here that some types of science currently being performed with HST that are critically sensitive to PSF shape, so it is important that work on assessing and characterizing these effects continue. In this area, efforts are underway to relate the Zernike values to the more familiar though less precise quantities such as FWHM and ellipticity in order to understand the impacts of optical variations on “real-world” science measurements.

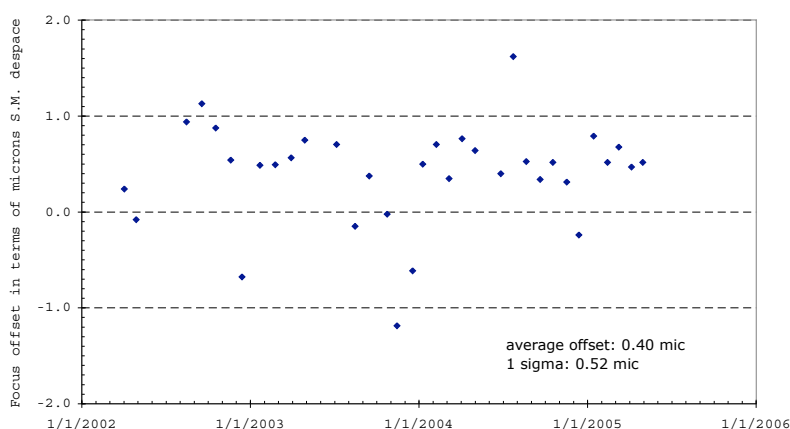
In the absence of a complete model for these variations, understanding the periods, timescales, and magnitudes also allows us to better assess the baseline state of HST focus at a given time, with the practical result of maintaining Observatory focus. A current focus assessment is discussed in Part 2.

Part 2. Focus Status

Since early 2002 routine focus monitoring was performed as monthly visits, obtaining parallel HRC and PC exposures over an orbit, from which phase retrieval is performed.

To establish confidence in the focus measurements from HRC, we compared results relative to the PC, which served as the primary focus monitoring SI since 1994 (Casertano 1995). The amount of non-parfocality between HRC and PC is found to be constant. Both the offset, and the scatter are ~ 0.5 microns at the SM, which are negligible and scientifically unnoticeable amounts (Figure 15).

Figure 15: PC minus HRC measured focus offset determined over the same orbital time period.



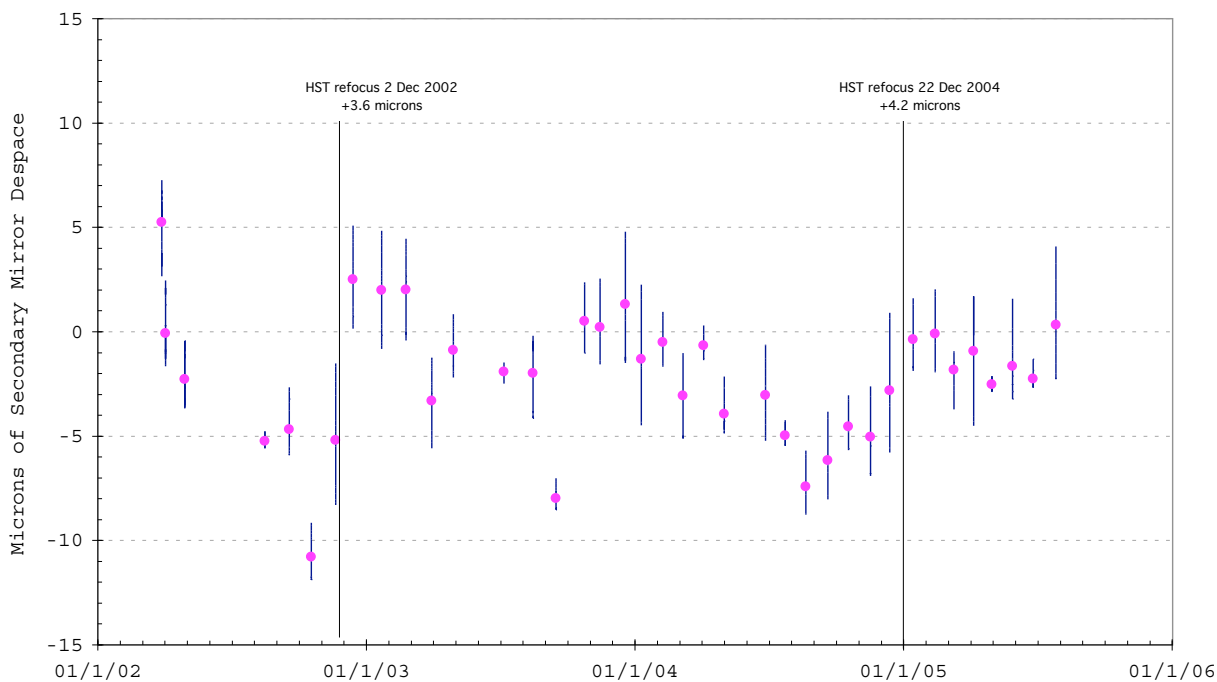
Establishing the fixed PC to HRC relationship allows us to present only HRC data to simply illustrate the Observatory's focus state. Figure 16 shows each visit from the monitoring program, with the red circles representing the orbital mean SM despace position relative to nominal focus and the blue lines represent the peak-to-peak spread of focus measurements during the orbit. As discussed in the first section of this report, the data within an orbit are highly correlated. Since only a portion of the entire breathing period is typically sampled, a more accurate method of establishing the orbital focus mean would be to fit the breathing model to the data. This would involve obtaining temperature data during the times in question to determine the amplitude, and varying the constant K in Equation 1 until a best fit to the sampled segment is obtained. One could then use the mean of the model as the orbital average. Because of the relatively small differences and the efficacy of current focus maintenance, this procedure is not typically performed. The last two refocusing SM moves are identified on the plot.

It is apparent that even with relatively large orbital swings, the focus maintenance has kept HST to within $\pm 5 \mu\text{m}$ of nominal focus most of the time. Also illustrated is the fact that knowledge of the seasonal period and its typical Autumn low point argued against requesting a refocusing despite the trend in the data from January to September 2003. STScI continues to maintain its conservative approach toward requesting focus adjustments, in order to avoid a "tail chasing" scenario involving a Mission Critical mechanism. This approach can be appreciated in the context of the complex behavior described in this report. Only once in the life of the Mission has the

need arisen to readjust the SM *toward* the PM in order to compensate for an overcorrection. This was the result of a “bump” in the desorption exponential causing elevated (more positive) focus around the time of Servicing Mission 2. This move, made in March 1997, can be seen in Figure 11.

It is clear that since the last refocusing in December 2004, we have remained near best focus. The last data point in Figure 16 was obtained late July 2005.

Figure 16: Means and spreads of focus monitoring data obtained with HRC roughly monthly since 2002. Mirror moves are indicated.



Appendix

A1. Phase Retrieval

Routine optical monitoring of HST is performed using IDL code to perform parametric (model-fitting) phase retrieval of a nearly in-focus PSF. The technique iteratively generates model PSFs and compares them with the observed data (Krist & Burrows 1995). The wavefront is characterized by the series of Mahajan Zernike polynomials modified for the 0.33 obscuration applicable to HST. They are listed below and discussed in greater detail in the OTA handbook (Burrows 1990). We currently solve only for the coefficients for focus (Z4) with PC data, while we solve for the coefficients for focus, 0°-astigmatism (Z5), 45°-astigmatism (Z6), x-coma (Z7), and y-coma (Z8) with HRC data.

The phase retrieval process produces an estimated wavefront described by the series:

$$(2) \quad W(r, \theta) = \sum_n c_n \alpha_n Z_n$$

where Z_n are the Zernike polynomials, c_n are the solved-for coefficients representing rms wavefront error in microns, and α_n = normalization factor sometimes seen included as part of the Zernike polynomial. For $n = 4$ to 8, $\alpha_n Z_n$ are given below:

$$\begin{aligned} \alpha_4 Z_4 &= 3.89 (r^2 - 0.55445) \\ \alpha_5 Z_5 &= 2.31 r^2 \cos 2\theta \\ \alpha_6 Z_6 &= 2.31 r^2 \sin 2\theta \\ \alpha_7 Z_7 &= 8.33 (r^3 - 0.673796r) \cos \theta \\ \alpha_8 Z_8 &= 8.33 (r^3 - 0.673796r) \sin \theta \end{aligned}$$

In the case of focus ($n = 4$) the c_4 coefficient can be expressed as:

$$(3) \quad c_4 = \frac{1 + m^2}{\alpha_4 8 F^2} \Delta_{SM}$$

where $F = 24 =$ HST focal ratio, $m =$ magnification $= F/f_{primary} = 24/2.3 = 10.43$.

Thus $c_4 = 0.0061 \cdot \Delta_{SM}$

A2. HST Metering Truss

HST's secondary and primary mirrors (SM & PM) are held in alignment by a thermally passive graphite-epoxy truss/ring structure called the Metering Truss (MT) because it exercises dimensional control in a thermally dynamic environment. The 4.9 meter MT consists of 48 2.1 meter tubular elements selected according to their measured thermal coefficients of expansion and then matched to the expected temperature variations for different locations in the truss in order to minimize bending. The Science Instruments (SI) are latched to the Focal Plane Structure Assembly (FPSA) which is mechanically interfaced to the MT. (Figures A1 & A2).

Figure A1: The MT and FPSA before integration.

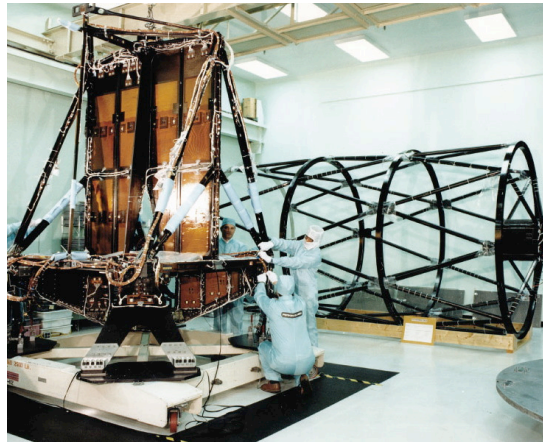
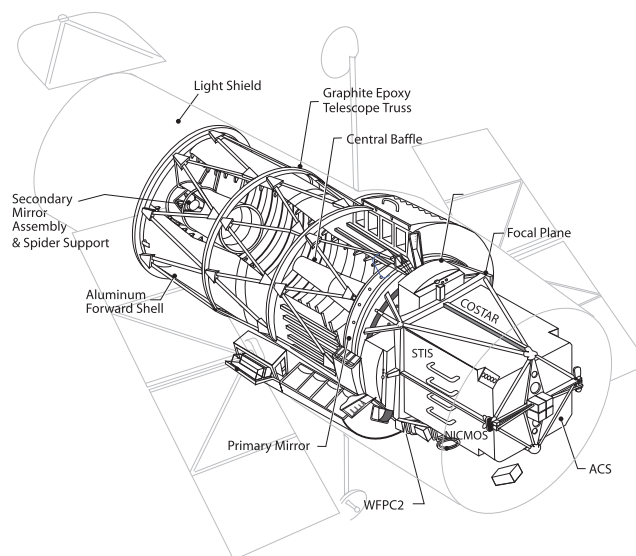


Figure A2: The MT and FPSA in relation to HST.



The *Space Telescope Systems Description Handbook* (Carter 1985) gives the requirements to which the HST metering truss was designed as follows:

Despace	< 118	microinches (~3 microns)
Decenter	< 394	microinches (~10 microns)
Tilt	< 2	arcseconds

The document does not elaborate on what time was assumed for the Mission life nor if this requirement was intended to specify limits throughout the entire Mission. Without knowing additional information about the requirement, it is difficult to assess the compliance with the specifications, but it would imply that tilts and decenters in the SM (if they were solely responsible for the observed coma and astigmatism) would fall well outside the tolerance. Investigation is continuing.

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