# Temporal optical behavior of HST: focus, coma, & astigmatism history

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## ABSTRACT

The focus of the Hubble Space Telescope (HST) has been monitored throughout the life of the observatory primarily by phase retrieval techniques. This method uses model fits to nearly in-focus Point Spread Functions (PSFs) to solve for coefficients of the Zernike polynomials describing focus, and in some cases coma and astigmatism. Here, we discuss what these data from the ongoing monitoring strategies and special observations tell us about modes and timescales observed in HST optical variations.

**Keywords:** Hubble, HST, space telescope, focus, aberration, desorption, PSF, phase retrieval, optical, Zernike

## 1. INTRODUCTION

It has been known since early in the HST mission that the observatory's focal length 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, improving our ability to measure the focus and infer the SM position through PSF properties. Despite several attempts[1], 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 be chaotic in nature.[2] 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.

Recent observations with Hubble's Advanced Camera for Surveys (ACS) High Resolution Camera (HRC) have enhanced our ability to measure additional image aberrations, such as coma and astigmatism. As with focus, the regular monitoring of coma and astigmatism is expected to yield an understanding of the origin of these aberrations and a better characterization of their orbital and long-term variations. Unlike the case of focus, however, the more complex motion of the SM or ACS optical elements required to induce such aberration changes also would, in most examined scenarios, cause a concomitant image motion which is not observed. Nonetheless, the understanding of aberration changes in ACS is an area of growing interest due to the sensitivity of a number of important science investigations to the morphology of the PSF. This is discussed in a complementary paper in this same volume.[3]

A list of conventions: throughout this report, unless otherwise stated, measured focus, coma, and astigmatism values are determined from a Phase Retrieval routine developed for HST by Krist & Burrows.[4] This approach solves for Zernike polynomial coefficients by iteratively fitting an observed stellar image. We follow the convention of focus=Z4, 0°astigmatism=Z5, 45°astigmatism=Z6, Xcoma=Z7, Ycoma=Z8, and may refer to the aberration by this Z-number as well as its name. Section 7.1 gives the polynomial definitions and additional details. We normally express the aberrations in microns rms wavefront error, however, for convenience, focus is converted to microns of physical separation between the HST SM and the Primary Mirror (PM), with this value referred to as *despace*. By historical convention, the zero point for despace is defined as best focus for the Planetary Camera (PC) channel of the Wide Field Planetary Camera 2 (WFPC2). Positive values indicate increased distance between the Primary & Secondary Mirrors. The HST structures comprising the PM, SM, and the metering truss that locates them is referred to as the Optical Telescope Assembly (OTA). The components of coma and astigmatism are defined with respect to the coordinate system of the particular detector from which the PSF is observed, rather than a common frame.

Finally, although we attempt to give background sufficient for an appreciation of the subject matter, we limit this paper's scope to the *apparent changes in determined aberrations over time.* Descriptions of the optical characteristics of the observatory can be found elsewhere.[3,4,5,6]

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# 2. ORBITAL BEHAVIOR (“BREATHING”)

## 2.1 Focus

A smooth change in measured focus locked to the HST orbital period was noticed very early in the Mission. Bély[7] coined the term “breathing” and established the 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 (Fig.13). The relationship is:

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

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, (FOC, a first generation HST science instrument), 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 ACS/HRC (Fig.1).

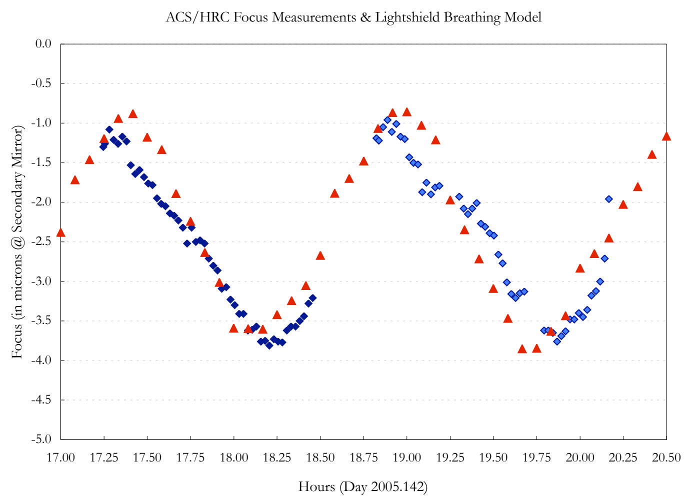



**Fig. 1:** Focus values determined from phase retrieval analysis of a point source in HRC over two HST orbits (blue). Overplotted in red are the modeled focus values using equation 1.

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 ACS/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 between Science Instruments (SI), a notable example being HST’s Near Infrared Camera and Muli-Object Spectrometer (NICMOS).[8] We point out that ACS replaced the FOC in the Axial SI Position 3 in the HST Aft Shroud (Fig.13), and their similar breathing amplitudes my relate to this commonality.

We plan to determine an accurate orbital scale factor for the focus model specific to ACS/WFC, which is the detector used in many studies involving weak gravitational lensing and/or the morphologies of barely resolved objects. Understanding the way such programs are impacted by coma and astigmatism changes (described in the following subsection) is valuable, and is examined further in this volume.[3]

## 2.2 Coma & Astigmatism

The Bély breathing model expresses the strong correlation between orbital focus swings and differences in the temperatures monitored near the SM support structure. This correlation is broadly interpreted as dimensional changes in such structures cycling over an HST orbit and producing oscillations in SM despace. We now explore how coma and astigmatism vary over orbital timescales and what that might tell us about cyclical induced tips, tilts, and/or decenters of the SM. Before the installation of the ACS/HRC, our ability to measure aberrations other than focus was limited. With HRC, we have a critically sampled PSF at wavelengths appropriate for phase retrieval. It is also well off-axis, making it more sensitive to certain types of optical misalignments.

In May 2005, as part of an on-orbit test to understand an operational pointing anomaly (described in this same volume)[9], 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 clear, repeated orbital pattern (Fig.2).

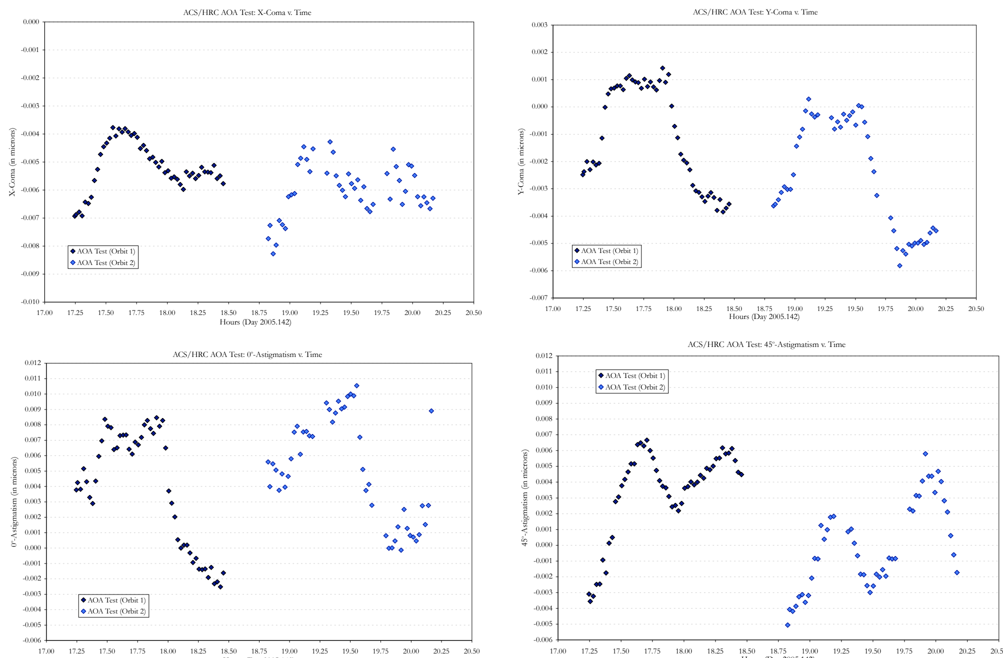



**Fig. 2:** X-coma, Y-coma, 0º-Astigmatism, and 45º-Astigmatism measured at HRC over two HST orbits (~90 minute observing period each orbit). Units are microns rms wavefront error.Peak-to-peak variations are roughly λ/100 for coma and λ/50 for astigmatism (at 550 nm).

In October 2005, as an enhancement to our routine focus monitoring observations, we began regularly obtaining HRC data with high temporal sampling similar to the data shown in Figure 2. The resulting aberrations, when input to a ZEMAX optical model of the HST OTA+HRC, can be used to gauge the combinations of tilts and decenters of the SM and/or ACS-specific optical elements that could produce them. Initial analysis based on a simplifying assumption that the observed aberrations are induced entirely by the OTA, indicates SM motions of ~50μm in tilt and decenter. This quantity is large enough to be physically implausible, and would induce shifts of the HST focal plane. By the nature of HST's Pointing Control System (PCS) this would not result in an image drift at the SI since the guide stars and science targets would undergo approximately whole-body motion, however it would result in HST's gyro-determined pointing data differing from the guidestar-determined data, and, with the exception of the now understood aforementioned anomaly [9], no such discrepancy seen. This suggests mechanisms other than the OTA are involved.

Alignment changes in the optical elements internal to ACS/HRC can be investigated using the same techniques, and a limited number of scenarios examined thus far again imply accompanying image motion. In cases where the aberrations are hypothesized to be induced by misalignments in the SI, the science target would now move relative to the guide stars, and would be directly observed to shift. In most but not all possible cases, the shift would be large enough to observe, yet we see no such image motion. Work is underway to further examine the possible sources of these apparent aberrations, and to investigate the role of non-optical phenomena such as detector-related effects on phase retrieval's reporting of coma and astigmatism (see Section 5.2).

Independent of the cause, the PSF morphology variations on an orbital timescale are likely real, and while the finely measured changes are quite small (equivalent to between λ/100 & λ/50 rms wavefront error at 550 nm) they are close to the level of detection by certain types of science measurements, so the importance of assessing and accounting for such effects should be understood. The phase retrieval routine is the most sensitive tool utilized to quantify the HST PSF morphology, but its precision comes at the cost of general utility. The high quality of its results require a short exposure (<< 96min orbit) of a bright but non-saturated, isolated PSF, at near-critical sampling, and in a rather limited range of wavelengths and S/N ratio. Thus it will be important to relate the wavefront error values resulting from phase retrieval to the more commonly employed though less precise measurements such as FWHM and ellipticity in order to understand the impacts of these variations on "real-world" science. [3]

## 3. MEDIUM-SHORT-TERM BEHAVIOR ("WANDERING")

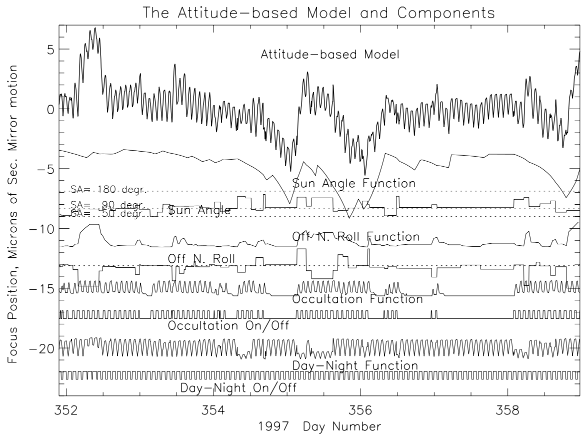
### 3.1 Focus

In the orbital breathing model expressed in Figure 1, 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 (normally 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 a geometry, known as *opposition*, where the planet is seen from earth to appear opposite the sun. It was found to be the result of an extreme sun angle (angle between the sun and the HST line-of-sight), in which HST pointed within a few degrees of the anti-sun direction for ~15 hours (~9 orbits). As the HST sun angle moves from a nominal 90º toward 180º, the temperatures at the metering truss and light shield drop, creating a negative focus state. Furthermore, when the sun angle increases beyond ~170º, 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 the breathing model 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, two models were produced 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.[1] 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 ("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 ("attitude-based" model, Fig.3). Although routine monitoring obtains focus data during roughly one orbit per month (sufficient for focus maintenance), there have been a number of long-duration science observations of targets suitable for phase retrieval analysis, and it has been such supplemental datasets that have allowed development of these models and the exploration of the timescale described in this section.

While the Hershey models were being developed and tested, they usually, but not always, performed well on the limited amount of measured focus data available (Fig.4). And though the models are no longer in use, the attitude-based model, however, remains significant for illustrating some of the operational drivers and physical scenarios that affect the HST dynamical response to heating.

Due to the difficulties in obtaining enough accurate focus data, meaningfully sampled for "training" the models, 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. Progress has been made, however, in the empirical modeling of PSF widths during science programs to calibrate and improve the results.[10,11,12,13,14,27]



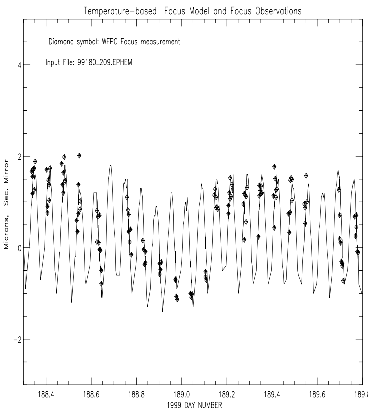




**Fig. 3: (left)** Medium-short-term focus wandering as predicted by the attitude-based model. The top curve models these excursions of HST focus which occur over scales of hours to days and can be large compared with the orbital swings (high frequency variations). Also plotted are the input parameters upon which the attitude-based focus model relies. Correlations with HST attitude history are apparent.

**Fig. 4: (right)** 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 at SM. Excursions of the orbital mean over the 1.5 days plotted was in this case less than the orbital range.

### 3.2 Coma & Astigmatism

The discussion 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, though much less is known about their behavior in this regime due to the lack of adequate time sampling for these more difficult measurements. Now that a larger set of archival ACS science data is accumulating, it should be possible to utilize suitable observations to supplement the monitoring, as is done with focus. The authors are currently examining such a promising dataset, which should yield over a week of continuous aberration measurements of targets at multiple field positions in the ACS/WF cameras.

Due to both detector and optical effects, ACS displays a field dependent PSF.[15] The changes in this field dependence as a function of temporal changes of aberrations in the input beam has been initially explored,[15,16] and can be better characterized by future analyses of such datasets as this week-long series of observations.

## 4. MEDIUM-LONG-TERM BEHAVIOR (SEASONAL & PRECESSIONAL)

### 4.1 Focus

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. The latter may play some role in affecting 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, and as a result, so slightly do its temperatures. A period consistent with this mechanism was suggested in focus data acquired during intensive optical monitoring of NICMOS in 1997.[17] This effect measured at NICMOS was reported to have an amplitude of ~+/-5 μm, which is comparable to, but somewhat larger than, typical orbital variations. 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 that the full-temperature and attitude-based models, which were developed using only OTA temperatures, predicted this period but with an amplitude of only +/-1μm, much less than that observed at NICMOS. This smaller amplitude, however, was found to best reduce residuals in WFPC2 focus data, suggesting that both the HST OTA and at least some of the SIs are sensitive to this precessional cycle.

On still longer timescales, eccentricity in the earth heliocentric 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.

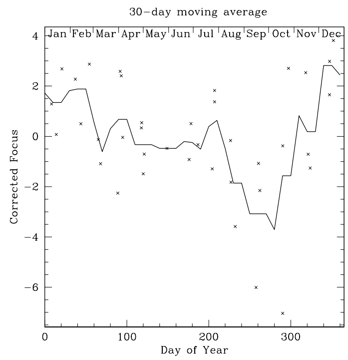
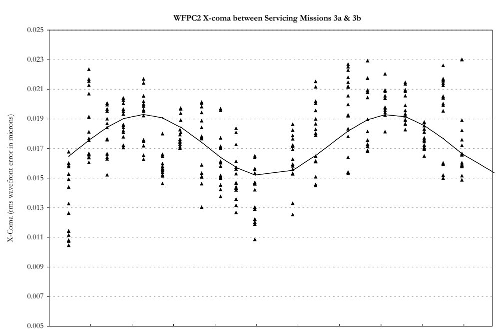



**Fig. 5:** Focus monitoring data obtained with HRC over the SI life (3+ years to date). Points are the means of measurements from individual visits executed roughly monthly. The curve is the 30 day moving average of those points. The plot is folded to 1 year.

### 4.2 Coma & Astigmatism

Both 0º-astigmatism in HRC and X-coma in PC show some sensitivity to the earth-sun orbital period, although an annual signature in the data is not clear throughout the monitoring from year to year. It is likely there are a number of different sensitivities involved in the aberrations' medium timescale behaviors, and the exact drivers and mechanisms by which the optical quality varies are not yet understood. Figures 6 & 7 show PC X-coma and HRC 0º-astigmatism over time periods which correlated well with an annual sinusoid. At other times, the behavior shows little annual periodicity, or even appears anti-correlated. Presumably, like the HST orbital effect, temperature inputs drive image changes due to a structural response. An important distinction is that with the HST orbital mechanism we know rather precisely both where the important thermal load is being applied, and the relationship between that and the resulting focus "breathing". Here, the effects of the much smaller seasonal changes in solar intensity are complicated by the attitude history of HST over that time and the open question of the locations of the important load points. A further understanding of the science impacts of these subtle aberration variations may guide the level of effort put towards a practical model characterizing them.



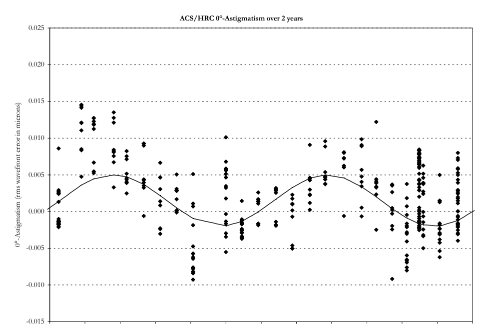




**Fig. 6**: **(left)** X-coma changes in PC measured between the last two HST servicing missions, with a best fitting sinusoid superimposed. Best fit was obtained with a period of one year and a peak-to-peak amplitude of 4 nm. The spread of values at a particular date is not due to measurement error, but the HST orbital variations described in Section 2. Though the correlation of groups of points makes statistical assessment difficult, an annual sinusoid best reduced the residuals. Units are in microns (rms wavefront error).

**Fig. 7: (right)** 0º-astigmatism changes in HRC over two years, also showing annual period. Peak-to-peak amplitude is 7 nm. Units are in microns (rms wavefront error).

# 5. LONG-TERM BEHAVIOR (DESORPTION)

## 5.1 Focus

The longest timescale in the HST optical system is a secular, predominantly exponential trend toward negative focus values. Since HST deployment in April 1990, the Secondary and Primary Mirrors have moved toward each other a total of ~150 µm. Although this is comparable to the thickness of a human hair, it has resulted 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 HST mission, prior to the observatory's first shuttle servicing, refocusings were performed frequently (2 to 3 times a year) and were usually of much larger magnitudes than today's.[18] It was common to command 20 µm of SM despace, as opposed to the 3 to 5 µm adjustments we now require every few years. Note that total SM despace magnitudes are well within the actuator range of many hundreds of microns.

The basic long-term behavior during roughly the first half the HST 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[19] 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. This trend was well characterized by a sum of exponentials[1,18] until roughly mid-1997 when the shrinkage began diverging from the model and became more discontinuous.[20] This date coincides with HST Servicing Mission 2 in February 1997. While transient effects of the shuttle environment during servicing missions have been detected in pressure/ion gauges residing onboard HST, the unpredictable truss shrinkage rate persists today (Fig.8)

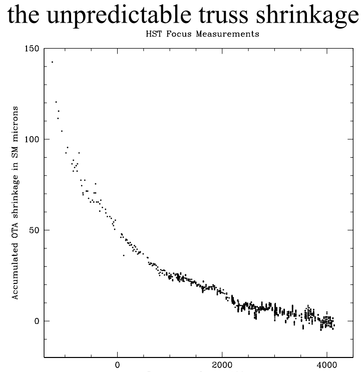
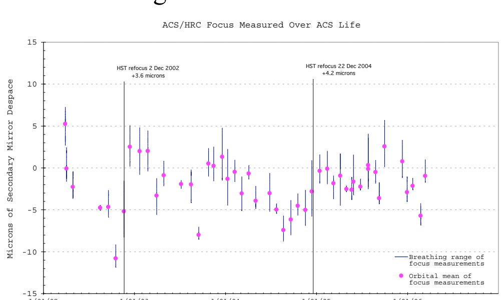



**Fig. 8:** Shrinkage of the HST metering truss since deployment, expressed in accumulated microns of negative despace of the SM. Desorption curve smoothly followed a function of exponentials until roughly day 1300.

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 the seasonal and other variations discussed. In the past five years, there has only been need for 2 refocusings of the observatory (Fig.9). However, careful monitoring is especially required since the focus state observed in this "low-desorption" phase of the observatory's life exhibits varying rates and discontinuities such as the March 1999 event seen in Figure 10.



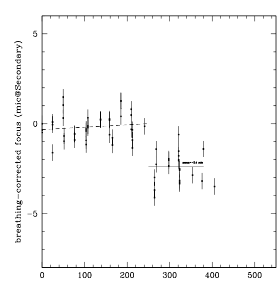




**Fig. 9: (left)** HST focus maintenance since the last servicing mission (March 2002). Date & amount of refocusings are identified. Vertical bars around points represent the total measured focus change over the sampled orbit. Points give the orbital mean. Units are microns of SM despace. Focus is seen here to usually lie within 5 µm of zero (< ~ λ/20 @ 555 nm)

**Fig. 10**: **(right)** Example of the discontinuities 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 interesting to examine coma and astigmatism, over the life of both ACS & WFPC2, done in the following section.

### 5.2 Coma & Astigmatism

The long-term behavior of ACS/HRC's coma and astigmatism shows overall stability with insignificant trends, while the WFPC2/PC coma shows insignificant trend in the x component but a constant linear increasing trend in the y component (Fig.11). PC's astigmatism variations as fit by phase retrieval are not as well determined as coma due to the greater impact of the camera's slight undersampling on that aberration's determination. It is not rigorously monitored or presented here. A discussion of ACS's on-orbit optical alignment and residual aberrations is given elsewhere.[5]

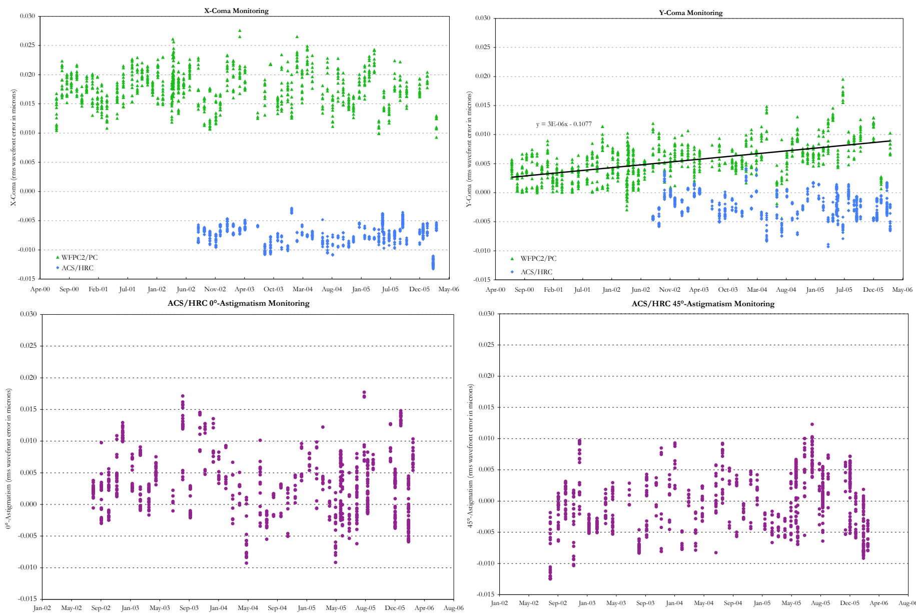



**Fig. 11:** Long-term aberrations plotted to the same scale (-0.015 to +0.030 µm rms wavefront error). Time baseline is to June 2000 for WFPC2 data and July 2002 for ACS. *Upper left panel:* coma in the x pixel direction as measured by HRC (blue) & PC (green). *Upper right panel:* coma in y pixel direction for HRC (blue) and PC (green; note linear trend). *Lower panels:* 0º & 45º astigmatism as observed in HRC.

Excluding for the moment the steadily increasing PC Y-coma, we might infer from the otherwise stable coma and astigmatism (as seen by more than one SI) that as the HST OTA metering truss settles, it is doing so in a way that is symmetric about its longitudinal axis; it could not be accumulating a bend or other deformation, as this would induce a trend in the measured aberrations by affecting SM tips, tilts or decenters, in a way analogous to the symmetric shrinking affecting focus via SM despace.

What might the increasing PC Y-coma be telling us? We observe that neither component of HRC coma indicate a trend, which argues against an OTA effect. We also note that the trend is quite linear and only seen in the Y pixel direction on PC, which is by convention the direction of the serial reads on the WFPC2 CCD detectors. Degradation over time of WFPC2 CCD's Charge Transfer Efficiency (CTE) was established early in the HST mission[21] and has been well studied since then.[22,23,24,25] CTE denotes the efficiency with which charge packets traverse arrays of pixels, being the fraction of charge which successfully moves between pixels during a single transfer. The pronounced decreasing CTE in WFPC2 is thought to be due to on-orbit radiation damage causing the trapping and later release of charge as an image is moved or "clocked" across the CCD to the readout amplifier. One of the results of this phenomenon is "tails" or trails of light seen on bright isolated targets, primarily in the +Y direction. CTE degrades at a rate very close to linear, and the integrated brightness of the resulting tails grows linearly as CTE decreases.

It is possible, perhaps even expected, that the CTE-induced distention of the PSFs we monitor is being characterized by the phase retrieval algorithm as Y-coma, since the algorithm must describe any PSF morphology changes only in terms of its free Zernike parameters: wavefront tip/tilt, focus, coma, and astigmatism. The very nearly linear increase in the Y-direction CTE tails observed in PC, and the linear increase observed in the PC Y-coma support this scenario.

Interestingly, while the ACS/HRC detectors also experience CTE degradation, we would not expect to see an analogous trend in its phase retrieval Y-coma measurements. Differences between WFPC2/PC and ACS/HRC's current detector CTE characteristics, and parameters such clocking rates and operating temperatures, mean that CTE tail strengths do not relate to total charge loss in the same way. A result is that for the same target signal-to-noise ratio and number of transfers, HRC exhibits less significant tails compared with PC.[26]

This possible detector effect on our optical monitoring, and the general issue of non-optical effects influencing aberrations analyses, is an important area to be investigated further, as are more ZEMAX optical scenarios, since both of these may relate to the previously discussed apparent lack of observed SI image or focal plane motion usually expected of even these very small aberration variations.

# 6. SUMMARY

An attempt has been made here to summarize the timescales and mechanisms at work which may affect HST's focus and optical alignment. HST's dynamical responses to thermal inputs are numerous and not fully understood. They remain subtle mysteries of the observatory. Fortunately, solid engineering and foresightful design has kept 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 described the observed behavior of instabilities in the HST PSF, which, while extremely low-level, do exist, and continue to drive the science considerations discussed in the many works already referenced.

# 7. APPENDIX

## 7.1 Phase Retrieval

Routine optical monitoring of HST uses IDL code to perform parametric (model-fitting) phase retrieval of a nearly in-focus PSF. Utilizing mirror maps based on previously determined mid-frequency wavefront errors, the technique iteratively generates model PSFs and compares them with the observed data. The wavefront error is characterized by the series of Mahajan Zernike polynomials[28] modified for the 0.33 obscuration applicable to HST. Our PSF fits normally involve focus, astigmatism, and coma (as well as the wavefront tilt, which is unused). The coefficients for the higher order Zernike terms contribute little and are fixed at established values or taken as zero. The definitions of the aberration polynomials of interest are given below. Detailed discussion of phase retrieval techniques and wavefront aberrations for HST is given by Krist & Burrows.[4] For a description of HST optical design and characteristics pre-launch, see Burrows.[6]

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

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

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

| | |
|---|---|
| $\alpha_4 Z_4 = 3.89 (r^2 - 0.55445)$ | focus |
| $\alpha_5 Z_5 = 2.31 r^2 \cos 2\theta$ | 0º astigmatism |
| $\alpha_6 Z_6 = 2.31 r^2 \sin 2\theta$ | 45º astigmatism |
| $\alpha_7 Z_7 = 8.33 (r^3 - 0.673796r) \cos\theta$ | X coma |
| $\alpha_8 Z_8 = 8.33 (r^3 - 0.673796r) \sin\theta$ | Y coma |

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

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

where $F$ = 24 = HST focal ratio, $m$ = magnification = $F/f_{primary}$ = 24/2.3 =10.43, and $c_4$ and $\Delta_{SM}$ are expressed in the same units. Thus $c_4 = 0.0061 \cdot \Delta_{SM}$

**7.2 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 forty eight 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 SIs are latched to the Focal Plane Structure Assembly (FPSA) which is mechanically interfaced to the MT (Figures 12 & 13).

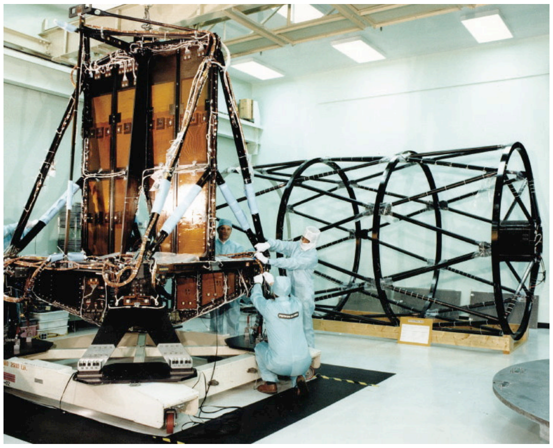


**Fig. 12:** The MT and FPSA before integration.

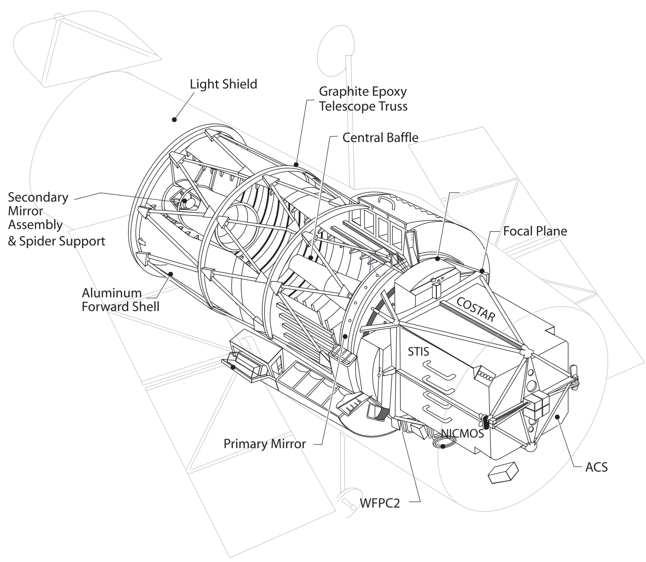



**Fig. 13:** The MT and FPSA in relation to HST.

The *Space Telescope Systems Description Handbook*[19] 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 service life nor if this requirement was intended to specify limits at all times throughout the entire mission. Without additional information about the requirement, and without a better understanding of the role played by the OTA/SM in our observed PSF changes, it is difficult to assess the compliance with the specifications.

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