

HST Focus & PSF Stability

Matt Lallo
for Telescopes Group

People Involved

PAST STAFF:

Pierre Bély, John Hershey, John Krist, George Hartig, Hashima Hasan, Chris Burrows, Kamel Houari, others.

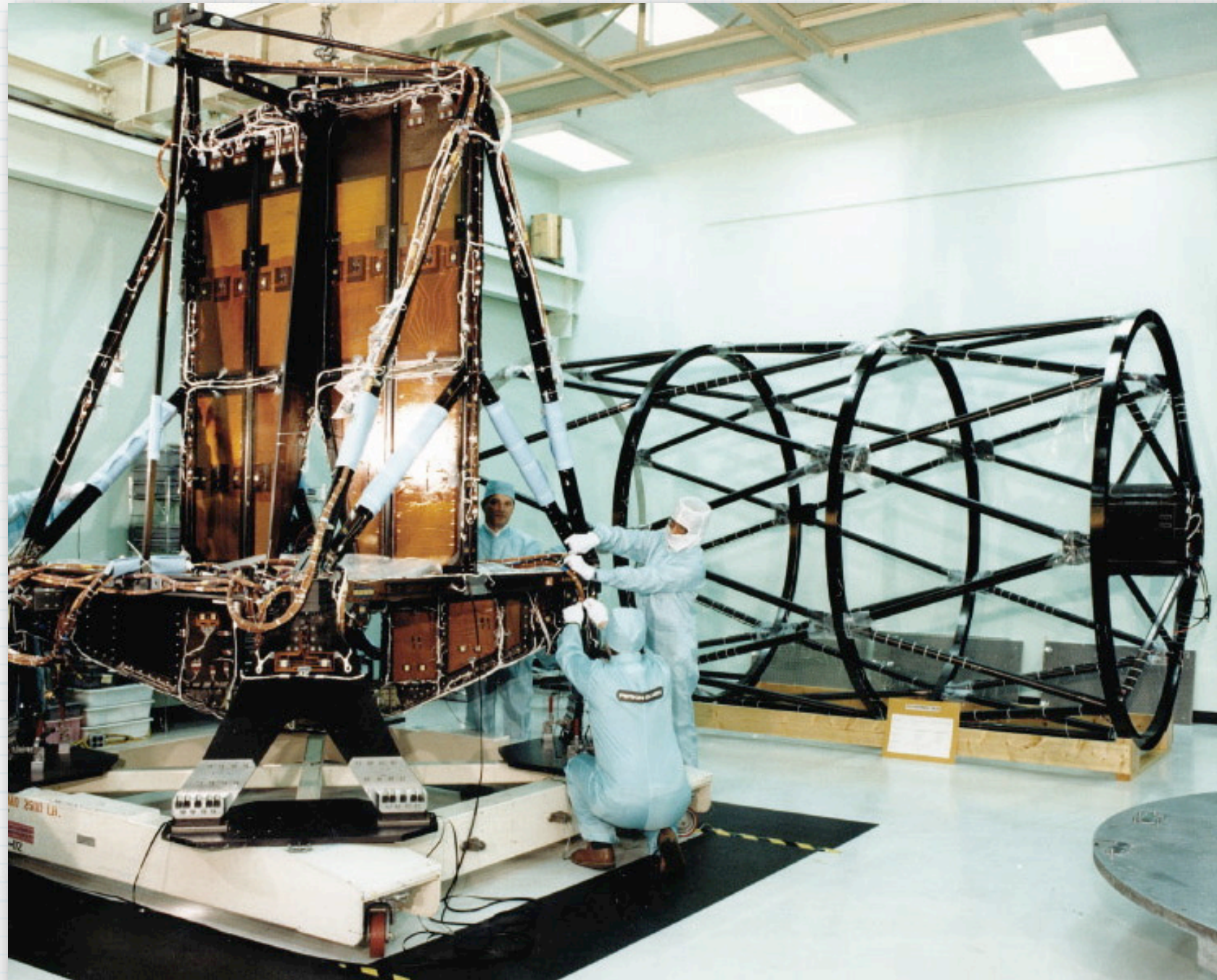
PRESENT STAFF:

Stefano Casertano, Russ Makidon, Ron Gilliland, Matt Lallo, Marco Sirianni, Kailash Sahu, Tommy Wiklind, Eddie Bergeron, Linda Dressel, Anton Koekemoer,, Daiana Di Nino, others.

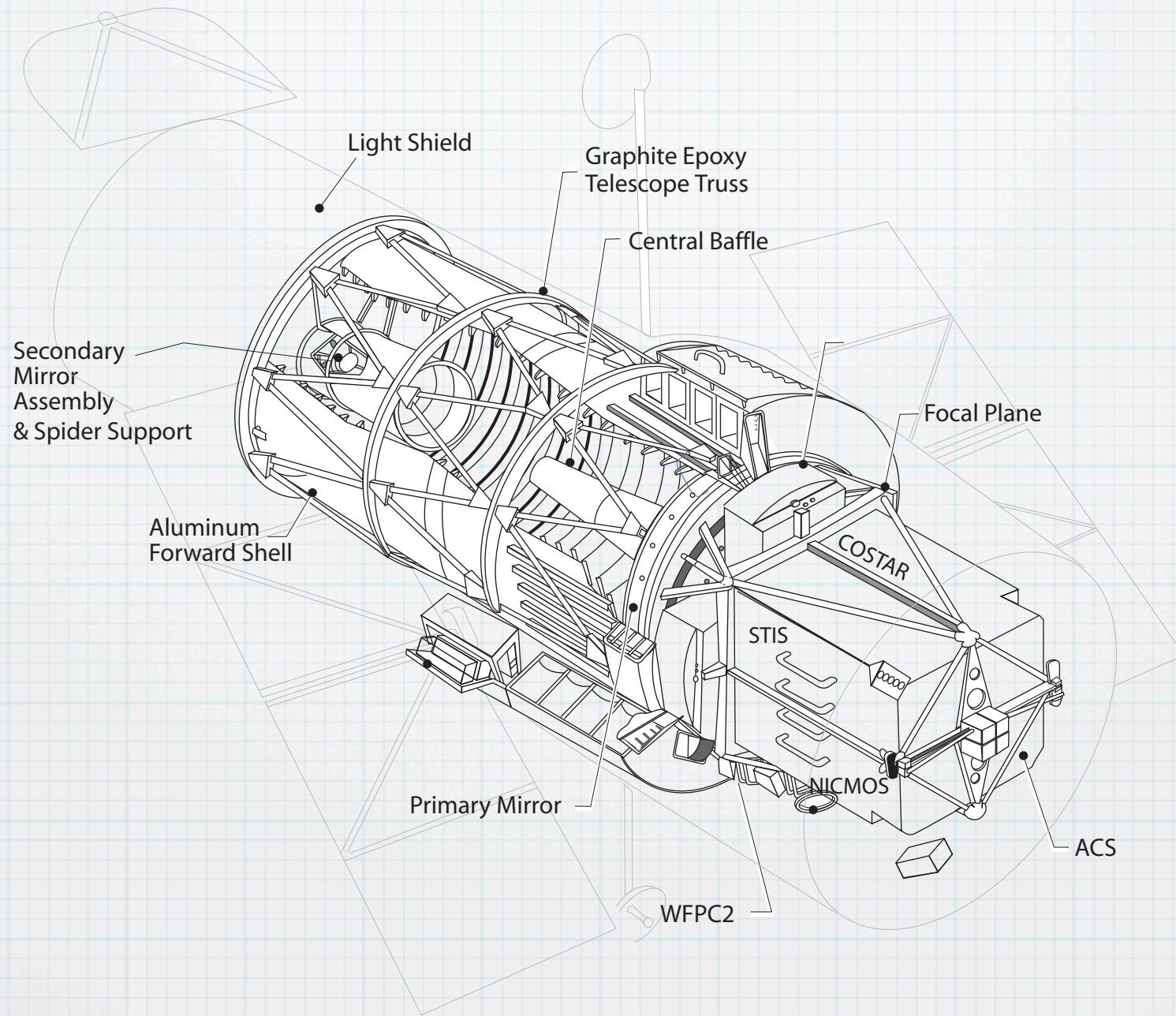
Notable GOs:

Jay Anderson (soon to be on staff), Jason Rhodes, others.


HST Optical Telescope Assembly (OTA)



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Timescales & Mechanisms

 HST experiences variations in focus, coma, & astigmatism (as measured through the SIs) on a number of different timescales (Lallo et al. 2005)

From shortest to longest:

1. Orbital (“breathing”)
2. Medium-Short-Term (days to weeks)
3. Medium-Long-Term (HST precessional to seasonal/annual)
4. Long-Term (truss shrinkage from desorption)

How we determine aberrations

STScI has used parametric phase retrieval (Krist 1995) to characterize the HST PSF quite accurately ($\sim 1\text{nm}$ rms WFE!) by iteratively fitting an observed PSF and expressing its morphology in terms of a Zernike polynomial series (Mahajan 1991):

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

where $\alpha_n Z_n$ is the normalized Zernike polynomials & c is the solved-for coefficients representing rms wavefront error in microns.

For $n = 4$ to 8 , an Z_n are given below:

$a_4 Z_4 = 3.89 (r^2 - 0.55445)$	<i>focus</i>
$a_5 Z_5 = 2.31 (r^2 \cos(2\theta))$	<i>0° astigmatism</i>
$a_6 Z_6 = 2.31 (r^2 \sin(2\theta))$	<i>45° astigmatism</i>
$a_7 Z_7 = 8.33 (r^3 - 0.673796r) \cos\theta$	<i>X coma</i>
$a_8 Z_8 = 8.33 (r^3 - 0.673796r) \sin\theta$	<i>Y coma</i>

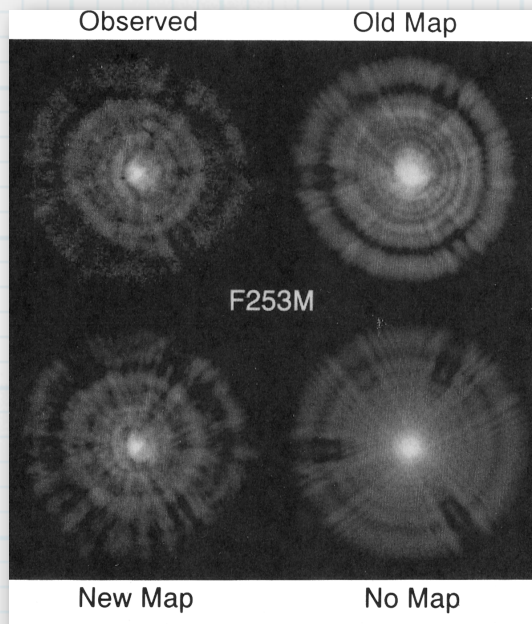
For HST, focus $c_4 = 0.0061 \cdot \text{Sec. Mirror despace in microns}$

How we determine aberrations

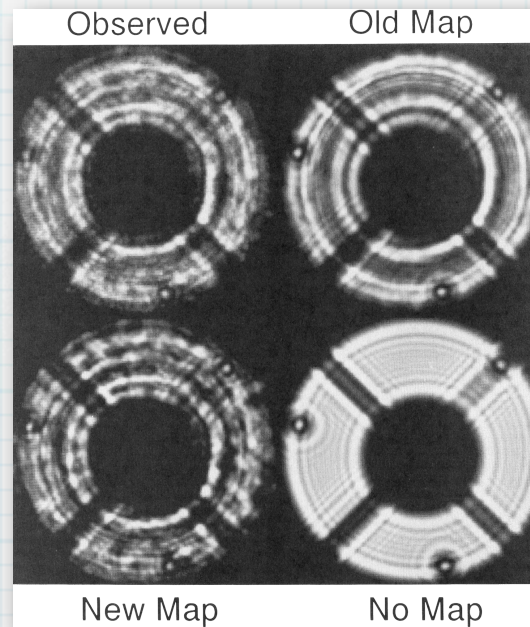
❏ *Question:* HST's PSF is always nearly in focus and relatively undersampled, so how can we get such good characterizations?

❏ *Answer:* Good mirror maps. During large (+/- 360 micron) secondary mirror sweeps early in the mission, mid-spatial frequency zonal ("polishing") errors were well mapped. Using this information, phase retrieval can accurately characterize the HST visible to NUV PSF remarkably well using only Zernike terms.

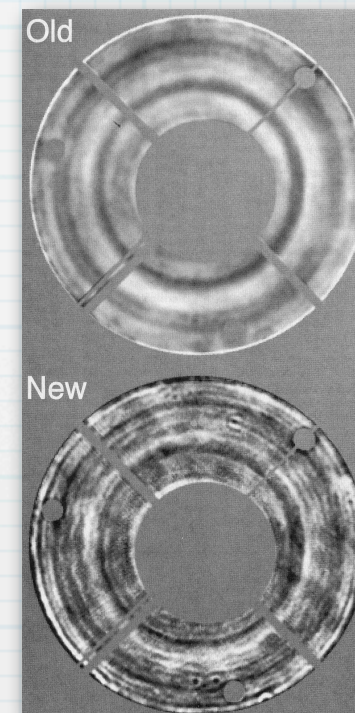
Model PSFs generated using known aberrations and three mirror maps: pre-flight, none, and on-orbit. Compare with observed PSF.



FOC at best focus and half-wave spherical aberration



WFPC2 at -360 microns from best focus



All figures on this page from Krist (1995)

Old & new Primary Mirror map (example from WFPC2, scaled between +/- 30 nm)

HST wavefront error budgets

- rms WFE for HST OTA (excluding the half-wave spherical!) is measured at ~ 15 nm, with majority (between 7 & 10 nm) thought to be coming from the “clover” aberration (Z9 & Z10) due to the PM supports, and most of the remainder due to the zonal errors. That's $\lambda/33$ at 0.5 microns.
- The rms WFE for HST+SI is greater, measured around 26 nm for HRC (Hartig) and between 50 & ~ 75 nm for WFPC2 (Krist & Burrows).
- So total combined system WFE for HST is somewhere between $\lambda/20$ & $\lambda/7$ depending on the SI. Variations around this nominal WFE, and its effect on the PSF follow.

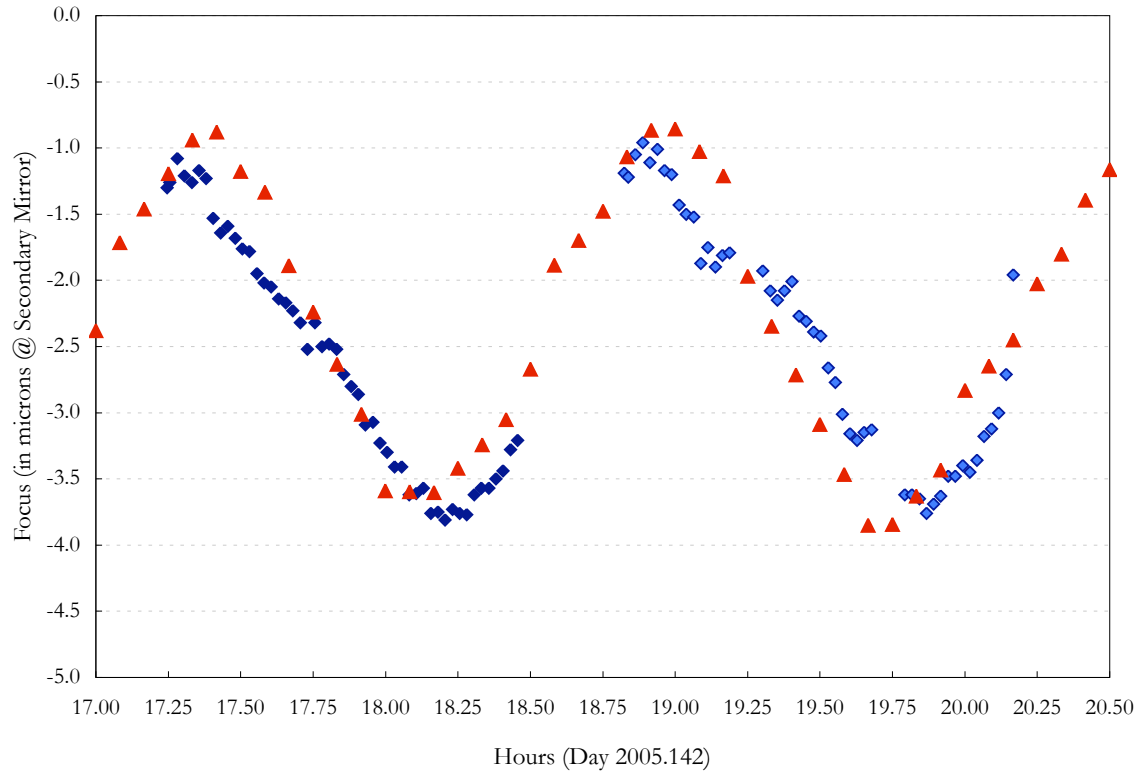
Orbital Effect on Focus (“breathing”)

HST focus displays a clear orbital period

- Identified in 1993 by P. Bely with FOC data.
- SM despace in μm empirically found = $0.7(\text{LS-MLS}) + K$
- Variable offset K reflects the secular zero point offset of the orbital mean focus.
- Scale factor known to vary slightly with SI, however recent (2005) HRC data shows excellent agreement with above model using original scale factor.
- Implies aft light shield temperatures are still primary drivers for orbital focus variations.
- Heating of the SM support structure is driven by primarily by IR from earth and secondarily by solar radiation.

Orbital Effect on Focus (“breathing”)

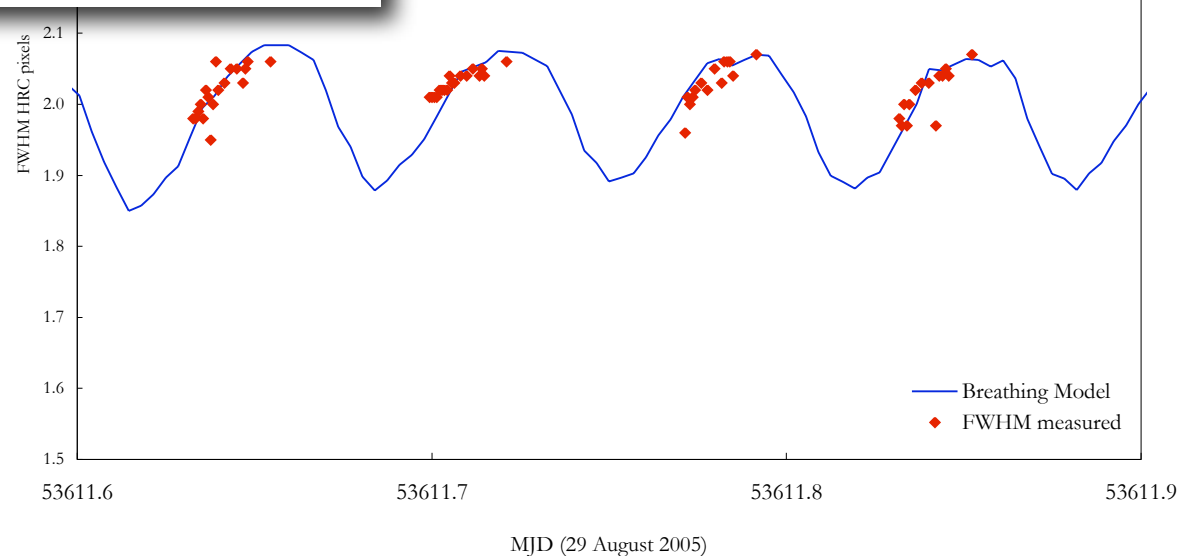
ACS/HRC Focus Measurements & Lightshield Breathing Model



Focus from phase retrieval (blue)
and Bély “breathing” model

FWHM measured in HRC plotted
with breathing model (Sirianni)

HRC TGSMOV PSF Measurements & Breathing model



Orbital Effect on Coma & Astigmatism

Coma & Astigmatism in HRC show an orbital signature

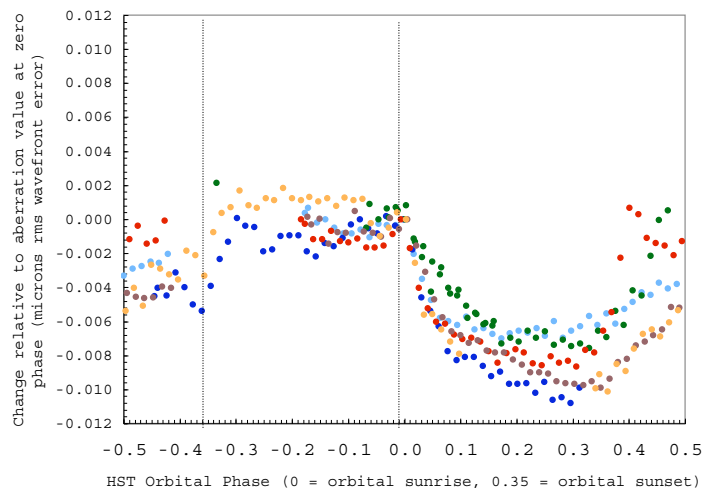
- total range of orbital variation ~ 10 nm (astigmatism) & 5 nm (coma)
- behavior is highly correlated with orbital phase and reacts strongly to HST day/night transitions.
- Response was thought to be too quick to be likely due to thermally induced optical misalignments.
- Aberration changes can be mapped back (non-uniquely) to tilts & decenters of optical elements. Makidon et al (2005) & Houari et al (2006) used ZEMAX models of OTA+HRC, to demonstrate that physical motions of optical elements would be extremely unlikely to reproduce the observed aberration changes without image motion, which is not seen, or without implausibly large physical motions.

Phase retrieval must characterize any PSF shape as a combination of the Zernike terms for which it is fitting. So the solved “aberrations” need not be optical in origin.

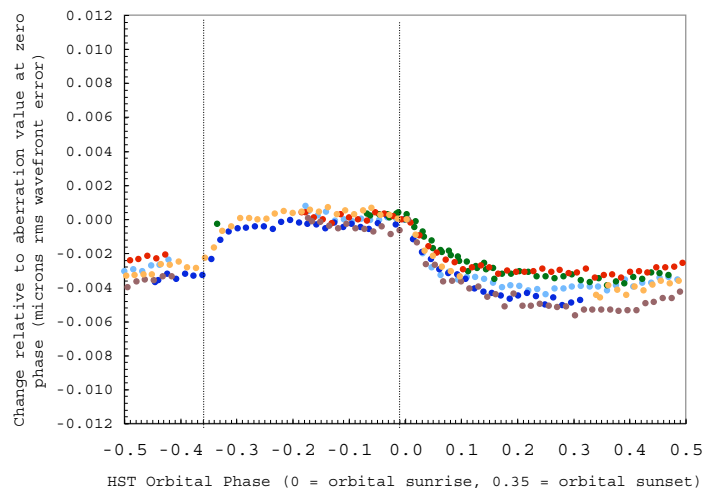
Orbital Effect on Coma & Astigmatism

Phased Aberration Changes (relative to orbital sunrise) on same scale, -12 to +12 nanometers

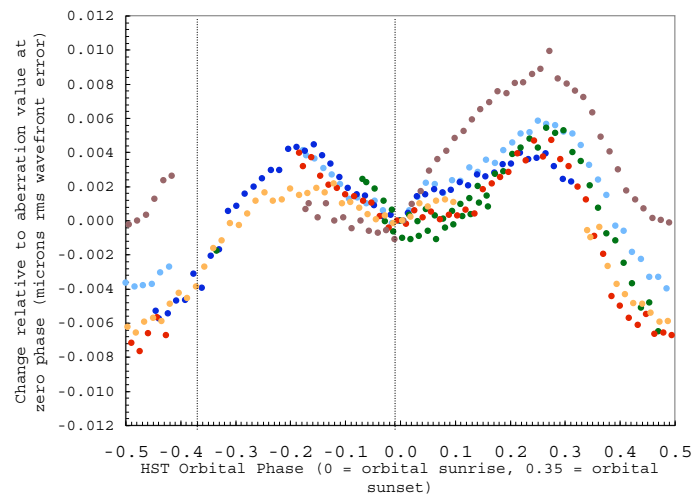
HRC 0deg-Astigmatism Change Over Orbit



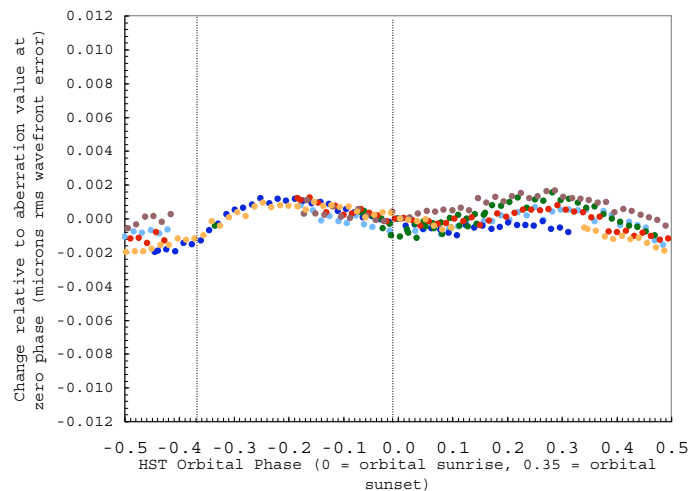
HRC Y-Coma Change Over Orbit



HRC 45deg-Astigmatism Change Over Orbit



HRC X-Coma Change Over Orbit

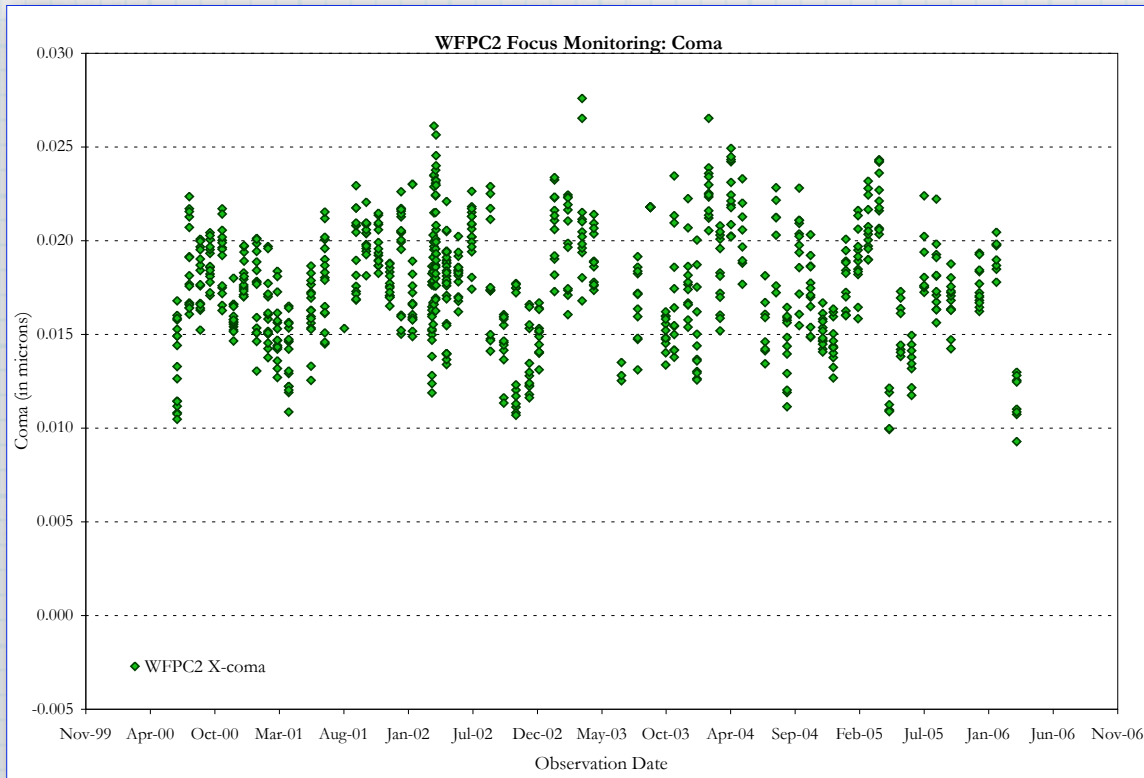


Apparent coma
& astigmatism
changes observed
in HRC data.

(registered to
orbital phase,
scale from -12
to +12 nm rms
WFE)

Non-optical causes of PSF shape change

Apparent x-coma in WFPC2/PC from 2000-2006

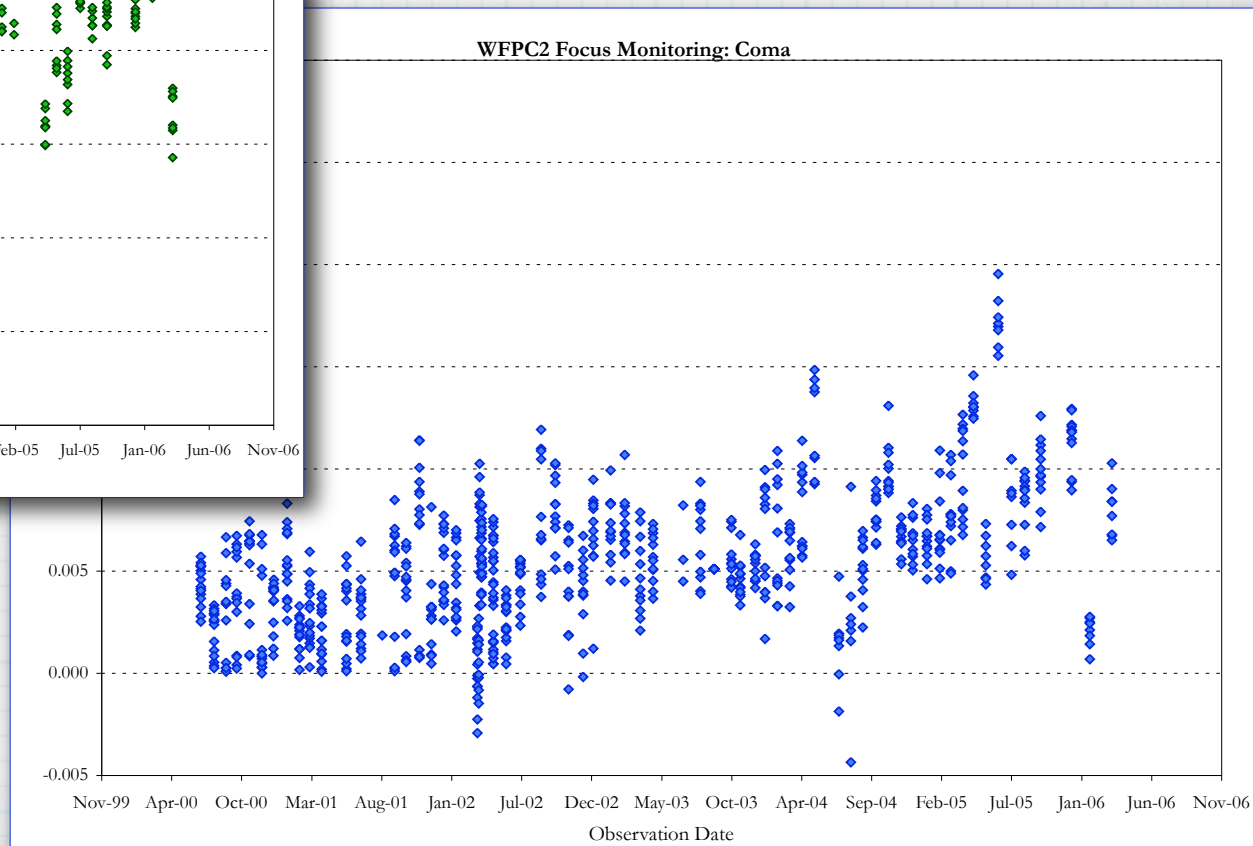


Long-term constant-rate trend of WFPC2/PC
“y-coma” likely an artifact of CTI increase
elongating the PSF.

Any PSF shape is described by phase retrieval as optical aberrations.

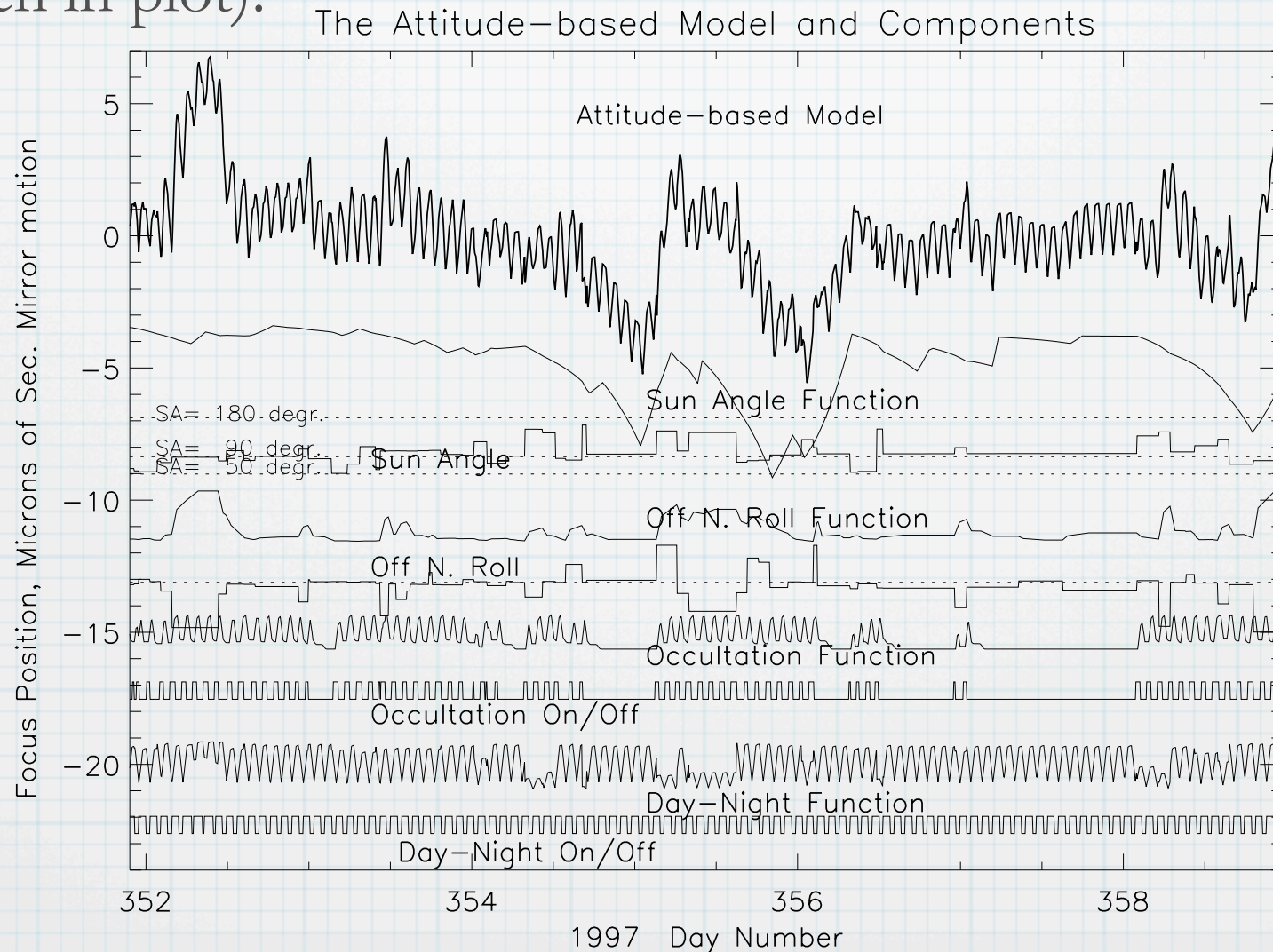
- CTE can look like coma
- Charge diffusion can look like focus, etc.

Apparent y-coma over same period



Medium timescale focus changes

- Focus behavior over one week as predicted by the defunct Hershey attitude-based model (Hershey 1997). Trends can be significantly larger than the orbital variation (high frequency seen in plot):



Models such as this (or its measured-temperature-based equivalent) have not been fully constrained by fits to sufficiently time-sampled observations, and are not known to include all the relevant parameters. Attempts have always suffered from gradual divergence from measurement over time.

Also see Sahu et al. 2007 & Di Nino et al. (in press)

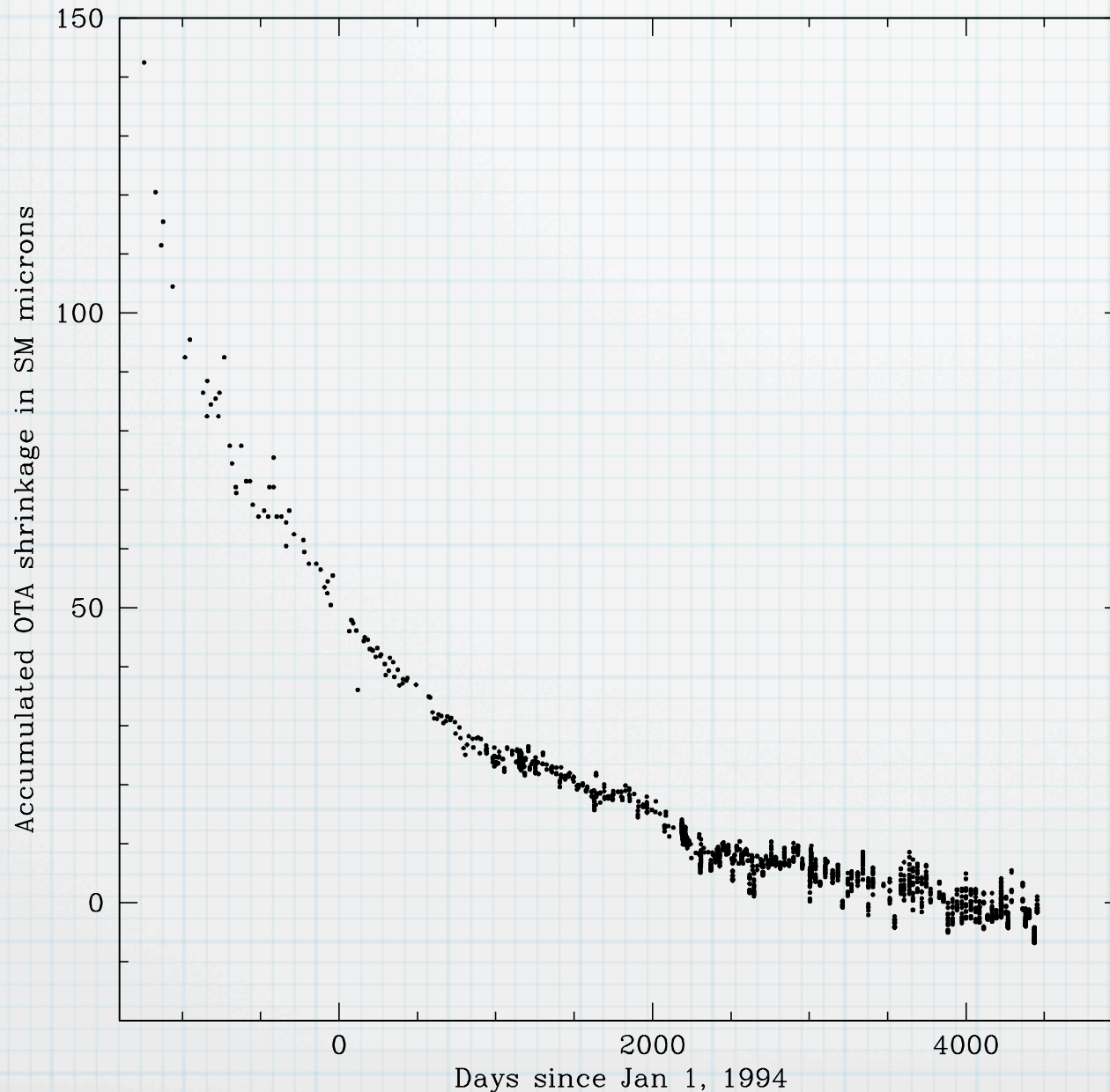
Long-Term Desorption

Long-term secular behavior is a persistent shrinking of OTA

- Since HST deployment in April 1990, the separation between the Sec. Mirror & Primary Mirror has decreased by over $150\text{ }\mu\text{m}$ (0.003% of the 5 meters separating them).
- There have been 21 documented SM despace adjustments to maintain observatory focus.
 - early in the mission, refocusings were frequent and of large magnitude ($\sim 20\text{ }\mu\text{m}$)
 - adjustments are currently rare (two since January 2001, $< 5\text{ }\mu\text{m}$ each)
- Shrinkage followed an exponential until late 1998 when the trend, though shallow, became more erratic.
 - exponential shrinkage understood to be due to desorption of the graphite epoxy truss in vacuum.
 - behavior in current epoch not well understood. There appears to be little publicly available data on graphite epoxy structures in space for 15 years.

Shrinkage of OTA Metering Truss over Mission Life

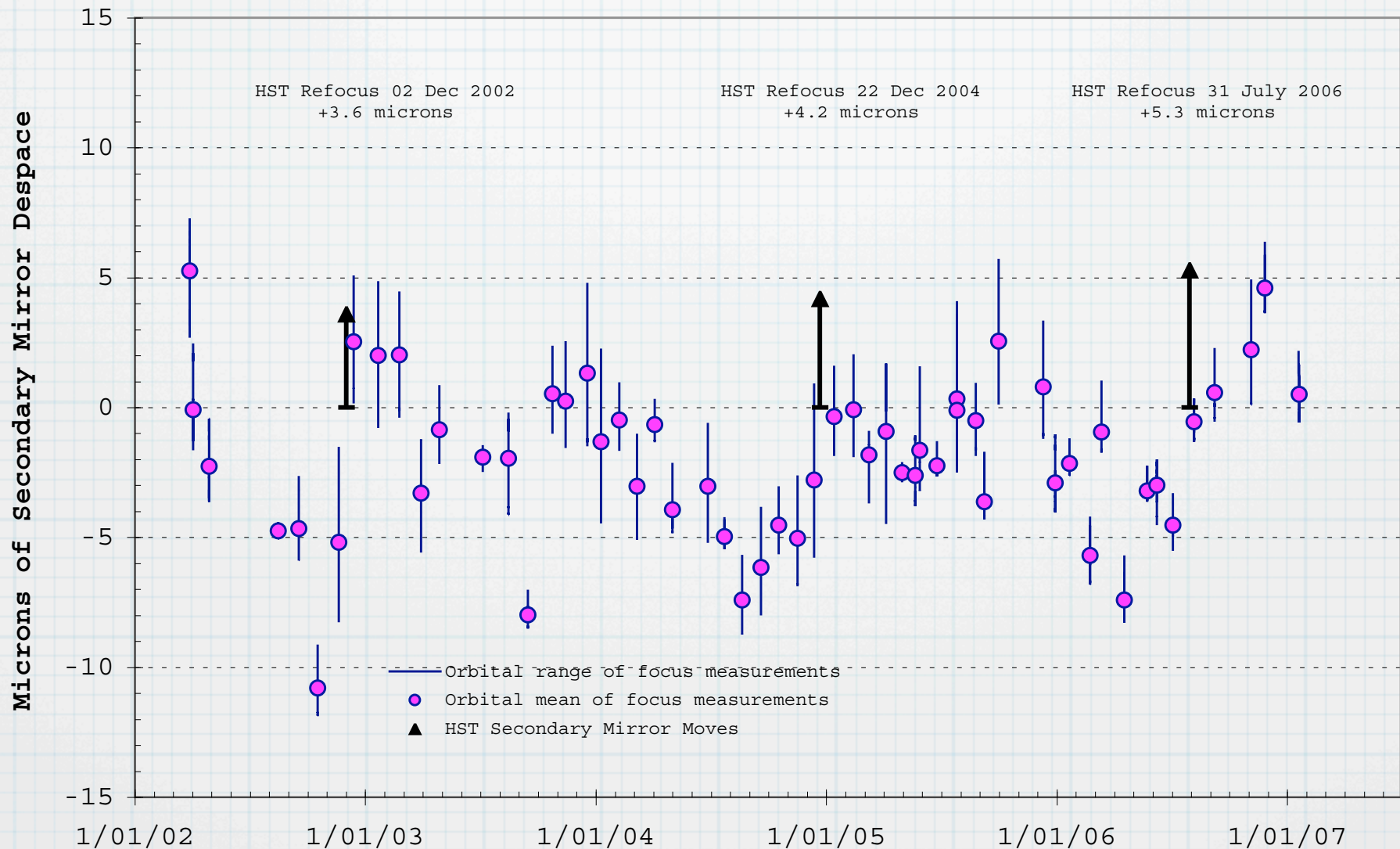
HST Focus Measurements



- 0.15 millimeters over 5 meters and 15 years!
- Deviates from function of exponentials. Rate in recent years slower but less predictable.
- Focus data complete to April 2006.

Why Do We Care? Part 1

We have always needed to maintain observatory focus within required range as dictated over mission life by the particular SI complement and the nature of the science. Recent desorption-compensating secondary mirror moves are shown below.



Why Do We Care? Part 2

- Understanding the PSF variations more subtle than overall focus trending can improve science in areas such as weak lensing and other programs where characterizing the shapes of barely resolved objects from point sources is fundamental. These rely on an extremely well-characterized PSF (Makidon et al. 2005, 2006)
- GOs like Anderson (2006, 2007), Rhodes (2007) and others at STScI have demonstrated successful procedures for fitting PSFs in fields with a significant number of stars over the larger camera fields of view. For example, Tiny Tim (Krist 1995) can generate model PSFs over the field at various assumed HST focus states. PSF grids/interpolations can be produced and empirically matched to large numbers of objects in the image. When combined with careful corrections for CTI, filter, and other effects, such procedures can give reasonably effective PSF characterization.
- Pursuing the holy grail of a complete predictive (attitude-based) or even descriptive (temperature-based) focus model should be balanced with the promise of practical approaches such as these.
- WFC3 exhibits greater PSF morphology change over the field than does ACS/WFC, while the interest in types of science requiring extremely well-characterized PSFs is on the rise. Our limited resources in this area should therefore be utilized only in the most effective ways.