

Modeling aberrations in the Advanced Camera for Surveys

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ABSTRACT

We present an analysis of the optical model for HST and ACS that shows the possible impact of misalignments of various optical elements on apparent image aberrations. The analysis was aimed at identifying possible causes for apparent variations in coma and astigmatism seen on orbital time scales in HST images. Results indicate that any combinations of mirrors and motions that reproduce the observed coma and astigmatism changes, also predict either large shifts in the image, which is not observed, or require unrealistically large movements of the elements.

1. Introduction

As part of the Focus Monitoring calibration program on the Hubble Space Telescope (HST), several well-exposed images of known point sources are obtained monthly through the High Resolution Channel (HRC) of the Advanced Camera for Surveys (ACS). Phase retrieval analysis of HRC images can consistently identify several Zernike components, including focus (Z4) as well as the components of coma and astigmatism (Lallo et al. 2006). For an overview of phase retrieval techniques used for HST, see Krist & Burrows (1995). Trending of these aberrations shows that they vary according to a systematic, repeatable orbital pattern, synchronized with the orbital day-night cycle—thus suggesting either a thermal or an electrical/power origin for the aberrations.

Orbital variations of the focus itself are well documented and are understood to be temperature-driven. The Bély breathing model (Bély 1993) established the strong correlation between the focus and the temperature of the Secondary Mirror (SM) support structure, and has since provided successful predictions of the amplitude and phase of focus variation during the orbit. However, coma and astigmatism are observed to vary much more rapidly than typical temperature variations at the time of entry into orbital day, with a pattern reminiscent of the Attitude

Observer's Anomaly (Van Arsdall et al. 2006), which was eventually determined to be caused by electrical power variations. Indeed, whereas focus variation due to breathing is smoothly sinusoidal, coma and astigmatism are very sensitive to the sunrise (Lallo et al. 2006). This difference of sunrise sensitivity suggests that heating of the secondary mirror spider supports is not a significant cause coma and astigmatism, as it is with focus.

An initial study of the possible origin of coma and astigmatism variations in terms of optical alignment was carried out in conjunction with the AOA investigation. Despite significant efforts, this study could not pinpoint a likely opto-mechanical origin for the observed aberrations, at least in the motions of the HST secondary mirror (Makidon 2005 & Zmek 2005). Here we present a more detailed and complete analysis of an optical model including both the HST Optical Telescope Assembly (OTA) and the ACS/HRC itself, and look at how possible misalignments of several optical components could be responsible for the observed aberrations. We also consider the possible impact of such misalignments on the observed image position, keeping in mind that no detectable image motion is observed during the orbit---which indicates that the relative alignment of ACS/HRC field of view and of the Fine Guidance Sensors (FGS) field of view does not vary measurably during the orbit.

At the basis of the present analysis is a detailed optical model of the HST OTA+HRC, provided by Makidon (2005) in the format used by the ZEMAX optical modeling software. Using ZEMAX, we can determine the optical aberrations generated when some parameters of an optical element, such as the conic constant or the position (tilt, decenter, despace), are modified.

In this report, we modify properties of the OTA SM, of the ACS M1, and of the ACS anamorphic corrector mirror (AM), and describe the results of these simulations.

For success, the model must explain the empirical observation that X-coma and 45° astigmatism appear to be closely correlated in the pattern of their orbital variation, as are Y-coma and 0° astigmatism. It must also reproduce the magnitude of the variations, which are 4nm ($\sim \lambda/100$ at 550nm) for each component of coma and 10nm¹ ($\sim \lambda/50$ at 550nm) for each component of astigmatism. Lastly it should also account for any observed positional shifts, or lack thereof.

Note that in this report all coma and astigmatism wavefront error magnitudes are rms.

2. The ZEMAX model for HST OTA+HRC

The ZEMAX software is an optical design program that can be used to describe and study the properties of complex optical systems. A detailed model including both the HST OTA and the ACS HRC was provided and adapted to our needs by Makidon (2005). ZEMAX includes a macro language which allows us to make modifications to the parameters of the model in an automated way. ZEMAX also produces spot diagrams and Zernike expansions of the expected point-spread function for each modified model. Spot diagrams are used to measure image positions for each model, and thus to determine how much image motion would be seen as a consequence of the modeled changes. Zernike expansions can be used to determine the predicted im-

¹ In this report, unless otherwise stated, aberration values refer to rms wavefront error

age aberrations for each case, which can then be compared to those measured from actual images. Some minor modifications were made to express the ZEMAX output Zernike values with the same conventions used by the Krist phase retrieval software.

2.1 Details of the optical model

The 2.4m aperture stop is situated 88mm in front of the vertex of the 2.4m, F/24 primary mirror (PM). PM radius of curvature is 11.042m with a conic constant of -1.0144 . The distance between the PM and the 30cm secondary mirror is 4.907m. The SM has a 1.358m radius of curvature and conic constant of -1.496 . Thus, the HST primary and secondary mirrors are hyperbolic. This Ritchey-Chrétien configuration is free of third-order coma and spherical aberration. However, the primary was polished with an incorrect conic constant of -1.0144 , rather than -1.0023 , resulting in the well-known spherical aberration of HST in the launch configuration. To counteract this error, all instruments installed on HST after its launch, called second and third-generation instruments, have been designed to correct spherical aberration. In HRC, three mirrors are necessary to correct spherical aberration and to image the object onto the CCD. To do so, a spherical mirror, M1, images the HST pupil onto the anamorphic mirror, AM, which is figured with the inverse conic error of the HST primary mirror. A third plane mirror, M3, sends the beam to the CCD (see Figures 1 & 2).

Figure 1: Zemax HST OTA+HRC model

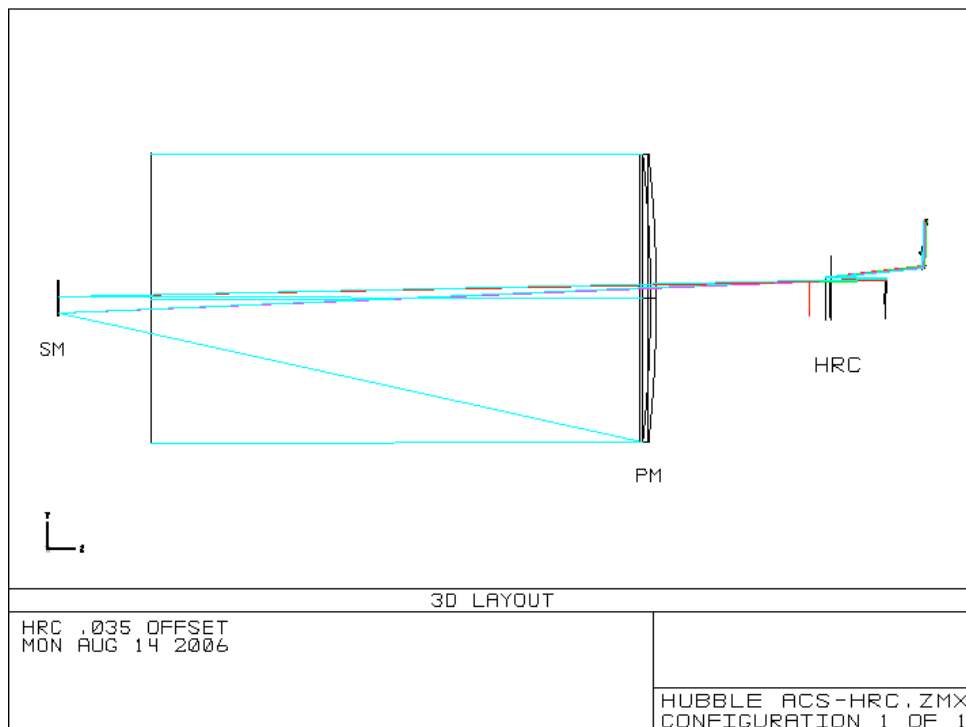
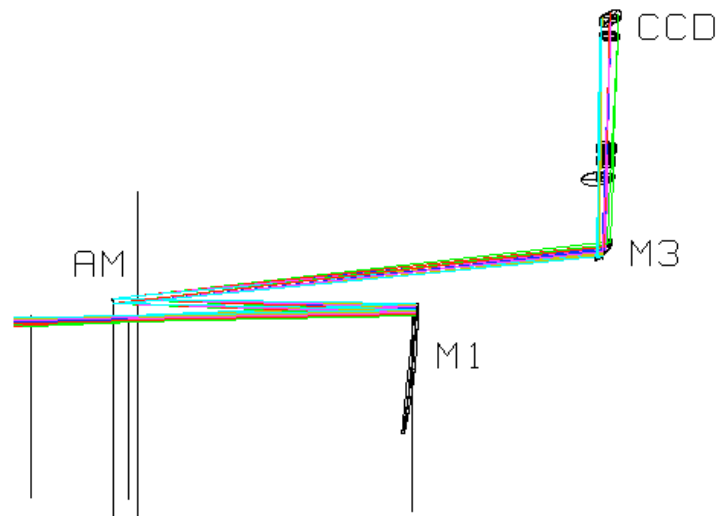


Figure 2: Zemax HST HRC model

3. Simulation with Zemax

Now we proceed to modify the parameters of the optical model, especially the positions of the secondary mirror, the M1 mirror, and the anamorphic plate, and record the variation of the components of coma and astigmatism with each. We note that, within the range of motions we consider, the aberration components change linearly with the applied positional perturbations (Figure 3). Thus the aberration changes induced by a given perturbation can be easily scaled from its maximum value presented and discussed elsewhere in this report. Table 1 provides a quantitative summary of the results presented in this section.

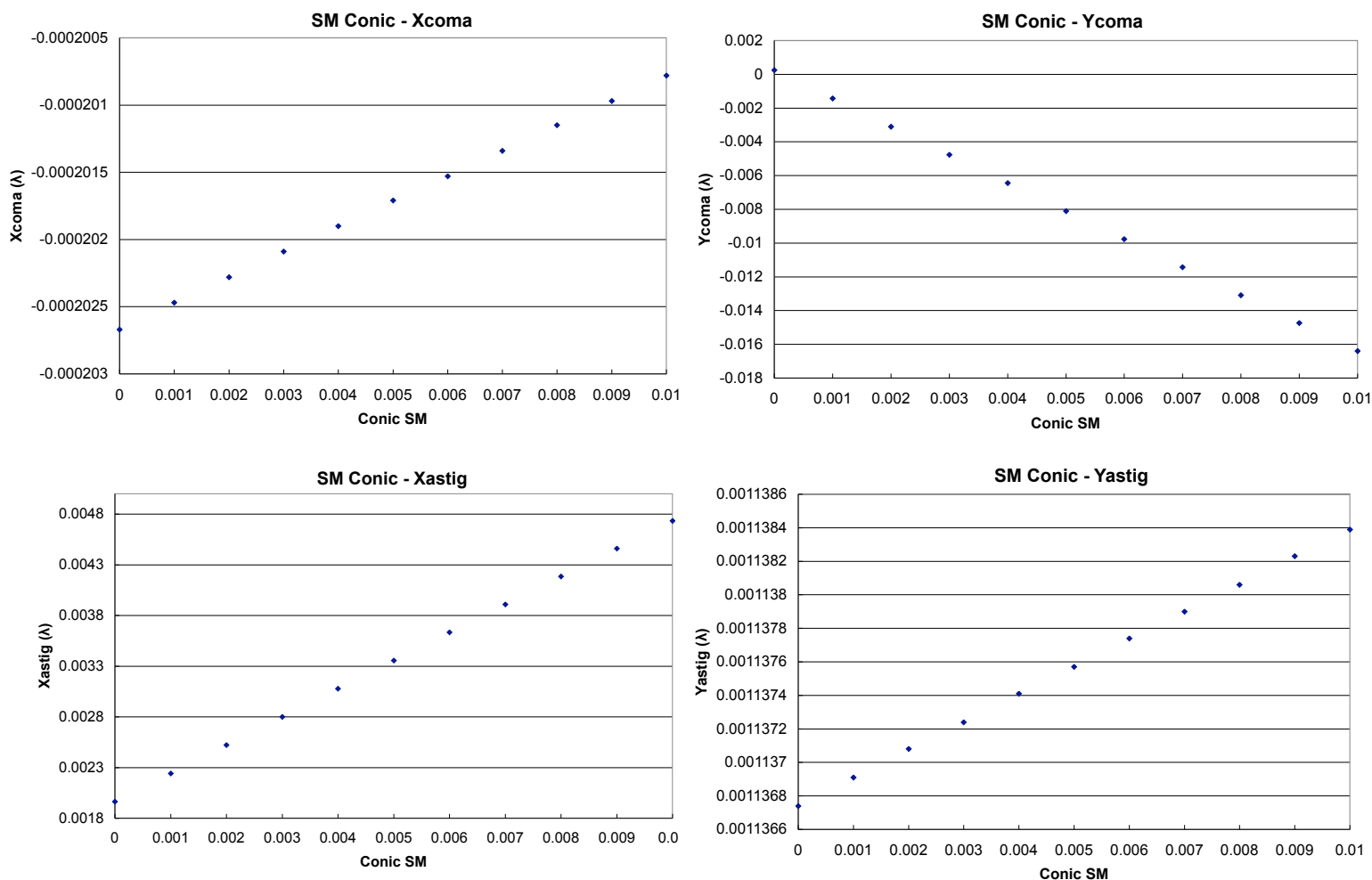
3.1 Secondary Mirror

Let us consider first the secondary mirror. We start with a possible distortion of the secondary, parameterized by a change in its conic constant, then we change its position by introducing despace, tilts, and decenters.

3.1.1 Conic constant

The conic constant of the secondary is -1.496 . We considered a modification by up to 0.010 in steps of 0.001 , which resulted in a maximum introduction of 14nm of Y-coma and -2nm of 0° astigmatism. Even such a large (and unlikely) change in conic constant fails to introduce an amount of astigmatism comparable to that observed.

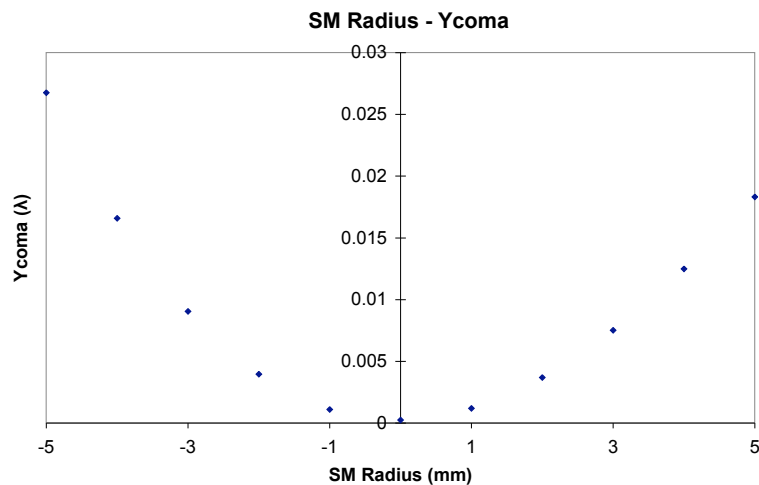
Figure 3: aberration changes vs conic constant



3.1.2 Radius of curvature

SM deformation could also lead to a change of the SM radius of curvature. We modified the radius of curvature so that the SM is put out of shape by $10\mu\text{m}$ at its edge. To do so, we made radius of curvature change by 1.5mm and found this mainly produces 2nm variation of Y-coma. This aberration would also be accompanied by an image motion of about 0.4mm at the HRC due to a change in OTA plate scale. This shift, which would equate to a 19 pixel drift of the target in HRC, is not observed.

We stated above that the aberrations' components change linearly with the applied motion or deformation. Radius of curvature was an exception. Aberrations are found to vary quadratically to first order with the radius of curvature change, and show some asymmetry. Figure 4 illustrates this relation for the example of Y coma, which is the aberration most altered by radius of curvature changes.

Figure 4: Y-coma change vs SM radius change

3.1.3 Despace

The “breathing” described by the Bély model is the secondary mirror despace oscillations due to the temperature change in its support structure. This represents an opto-mechanical change in the telescope whose relationship with measured temperatures has been reliably determined. Typical orbital variations of the SM have a peak-to-peak amplitude of $5\mu\text{m}$, and induce a focus wavefront error at the focal plane of about 30nm .

However, a despace of $10\mu\text{m}$ in either direction, four times larger than typically seen in the Bély breathing, produces negligible variations in coma and astigmatism, less than 0.1nm , thus showing that the well-known despace motion of the secondary is not responsible for the orbital variations in aberrations.

3.1.4 Decenter

We have seen that the secondary mirror can move by a few microns. What if it also experiences off-axis motions of comparable amplitude? To test the consequences of such motions, we decentered the SM by $10\mu\text{m}$ in X and Y respectively. This level of decenter causes 3nm of X-coma and Y-coma respectively, about a factor of 2 smaller than observed. Although a decenter might be suspected of producing astigmatism due to the off-axis position of the HRC in the focal plane, we find in fact the total amount of astigmatism induced by $10\mu\text{m}$ of decenter is only 0.3nm . We also would expect from this an image motion of about 0.1mm or 5 HRC pixels, although without understanding the exact nature of the predicted shift, it is not possible to say how much of this might be removed by the process of HST FGS guiding.

3.1.5 Tilt

We tilted the SM by 0.01° , which corresponds to a physical motion of $25\mu\text{m}$ at the edge of the mirror. This level of motion is implausible, but the linear relation between distortion and aberration means that we can scale the answer to the observed level of aberration. We find that a tilt of 0.01° in X (respectively Y) induces variation of 29nm in Y-coma (respectively X-coma), along with a 20nm change in 0° astigmatism (respectively 45° astigmatism). A more realistic motion of $5\mu\text{m}$ could induce about 6nm of coma, close to the level observed in the data, but would produce only about 4nm of astigmatism, one-third of that observed.

The corresponding image motion is large, $\sim 1\text{mm}$, but for the case of SM tilt, the image shift is the result primarily of a displacement of the entire focal plane, including the guide stars in the Fine Guidance Sensors. Since the target to guidestar relative positions would be to first order invariant, negligible target motion would be observed. There would, however, exist a discrepancy between attitude data from the HST gyros (vehicle pointing) and FGSs (optical axis pointing). The known gyro to FGS discrepancy is believed to be much smaller than would be expected from this scenario of SM tilt. Exact amounts are being determined.

So while SM motions of amplitudes comparable to the breathing can explain the amount of coma observed in the images, they do not reproduce the observed astigmatism, and do not appear to be compatible with the good agreement between vehicle and optical axis pointing.

3.1.6 Breathing

The well known oscillations along the secondary mirror axis vary over an orbital period as do coma and astigmatism seen in ACS/HRC, but is this a cause of observed coma and astigmatism? The study of the position along the axis of the SM (despace) did not support this hypothesis. Indeed, Zemax calculations concluded that the amount of coma and astigmatism due to a despace by $10\mu\text{m}$ would be smaller than 0.1nm .

Regarding despace, a simple check of Zemax model fidelity showed that $1\mu\text{m}$ SM despace corresponds to a focus wavefront variation at the focal plane (Z4) of 60nm , close to the well-established value of 61nm , within 1.7%.

3.2 HRC mirror 1

Motions of the optical elements inside HRC are more strictly constrained by the image motion they imply, as those elements are not common to the FGS. Therefore any image motion resulting from perturbations of the HRC optical elements would be directly reflected in the science data.

As we did with the SM, we assume the HRC mirror M1 radius of curvature can be altered by a deformation of the mirror and speculate it could be put out of shape by $5\mu\text{m}$. We made a corresponding radius of curvature change of 1mm and found it induces 23nm variation of Y-coma and

1nm variation of 0° astigmatism. This modification also produces an image motion of about 0.1mm (5 HRC pixels) which would be obvious in observations, but which is not seen.

Despacing the M1 by $10\mu\text{m}$ produces virtually no coma or astigmatism changes.

Decenters by $10\mu\text{m}$ in X (and respectively Y) direction induce 2nm of Y-coma (and respectively X-coma), values approximately half those observed, while inducing no astigmatism. The corresponding image motion is approximately 1 pixel, which would also be easily detectable in HRC exposures. Therefore decenters of M1 are not capable of accounting for the observed coma and astigmatism.

Finally, we find that tilting M1 causes significant coma and very little astigmatism. A tilt of 0.01° , corresponding to $18\mu\text{m}$ at the edge of the mirror, in the X (and respectively Y) direction induces 38nm of Y-coma (and respectively X-coma), and 1.5nm of 0° astigmatism (and respectively 45° astigmatism). The induced image motion is large, 0.5mm.

The lack of astigmatism production and implied image motions rule out M1 motions as the sole cause of the observed aberration variations.

3.3 HRC anamorphic mirror

3.3.1 X & Y parameters

The asymmetric AM's curvature is characterized with an X & Y parameter, whose values are 3.7×10^{-4} and 3.6×10^{-4} respectively. We put out of shape HRC AM by modifying X parameter by 1×10^{-6} . This produced 20nm of 0° astigmatism but only 1nm of 45° astigmatism, and no coma. Modifying the Y parameter by the same amount induced no coma or astigmatism.

In both of these cases, no image motion is induced by the deformations.

3.3.2 Position, decenter, tilt

First, we changed the AM position by $10\mu\text{m}$ and found this motion does not induce noticeable aberration changes. Then we decentered the SM in the X (and respectively Y) direction by $10\mu\text{m}$ and found this affects X-coma (respectively Y-coma) by 2nm. Orbital timescale coma variations are 5nm, so the AM would have to be decentered by a rather large $25\mu\text{m}$ to induce this aberration. Finally, we tilted the anamorphic mirror by 0.01° which corresponds to $1.7\mu\text{m}$ motion on each side of the mirror, and found tilt induces virtually no coma or astigmatism, but a significant image motion of 0.5mm.

Table 1: Aberrations induced by perturbations

Parameter modified	Amount of modification	Coma (nm)		Astigmatism (nm)		Image motion (mm)	
		X	Y	0°	45°	X	Y
OTA Secondary Mirror							
Conic constant	0.01	0	13.8	-2.3	0	0	0
Radius of curvature	1.5mm	0	1.7	0.2	0	0.133	-0.365
Despace	10 μ m	0	0	0	0	0	10 ⁻³
X Decenter	10 μ m	2.9	0	0	-0.2	0.23	0.09
Y Decenter	10 μ m	0	2.9	0.3	0	-0.1	0.27
X Tilt	0.01°	0	29.2	20	0.5	-2.34	6.4
Y Tilt	0.01°	-28.5	0	-0.7	19.8	-5.47	-2
ACS HRC Mirror 1							
Radius of curvature	1mm	0.1	-22.7	-0.8	0	0.107	-26 \times 10 ⁻³
Despace	0.01 μ m	0	0.1	0	0	0	-10 ⁻³
Y Decenter	10 μ m	2.3	0	0	0	26 \times 10 ⁻³	9 \times 10 ⁻³
Y Decenter	10 μ m	0	2.3	0	0	-11 \times 10 ⁻³	30 \times 10 ⁻³
X Tilt	0.01°	0	37.7	1.4	0	-0.178	0.486
Y Tilt	0.01°	-37.8	0	-1.2	0.3	-0.417	-0.15
ACS HRC Anamorphic Mirror							
X parameter	10 ⁻⁶	0	0	-20.6	-0.8	0	0
Y parameter	10 ⁻⁶	0	-0.1	0.2	0.8	0	0
Despace	10 μ m	0	-0.1	0	0	10 ⁻³	-10 ⁻³
X Decenter	10 μ m	-2.2	0	0	0	9 \times 10 ⁻³	3 \times 10 ⁻³
Y Decenter	10 μ m	0	-2.2	0	0	-4 \times 10 ⁻³	10 \times 10 ⁻³
X Tilt	0.01°	0	0	-0.2	0	0.17	-0.45
Y Tilt	0.01°	0	0	0	-0.2	0.4	0.15
Z Tilt	0.01°	0	0	0	-0.1	0	0

4. Combinations of optical elements

Results described above indicate that a single movement or a deformation in one particular optical element cannot be the cause of the observed variation of apparent coma and astigmatism over orbital timescales. It is also unlikely that motion in an optical element motion would be constrained to the X direction or Y direction. We now describe aberrations resulting from combination of motions and deformations in combinations of our three mirrors.

Tests have been carried out on Zemax to see how aberrations evolve when we simulate several movements and deformations in a mirror independently of other optical elements. All those tests conclude that the total amount of aberrations induced is the sum of aberrations induced by

each motion and each deformation taken individually. Likewise, for aberrations induced when several optical elements are involved in the simulation, the amount of aberrations induced when more than one mirror is perturbed proves to be the sum of aberrations produced by each mirror taken separately.

This linear system of independent orthogonal relationships for most of the tabulated values, along with the fact that the Zernike coefficients considered vary linearly with the amount of motion or deformation (except the radius of curvature change which seems to vary quadratically), allow us to readily combine perturbations and elements to attempt to reproduce the observed aberrations.

5. Solutions

This underdetermined linear system has many formal solutions, but their number is in practice limited by constraints. If we consider the solutions involving physically plausible perturbations (assumed here to be no element distortion, and only motions less than $15\mu\text{m}$, about double the amount the SM moves during an unusually large breathing cycle), then the solution best fitting the observations was found to be a combination of tilts of the OTA SM and the ACS M1. By tilting the secondary mirror by 0.005° in X and 0.005° in Y, and by tilting the M1 by -0.025° in X and -0.005° in Y, we can reproduce coma and astigmatism consistent with that measured in the actual data. These tilts correspond to a movement of the secondary of $13\mu\text{m}$ at its edges and a movement of the M1 by $9\mu\text{m}$ at its edges. These motions induce a variation of 4.6nm for X coma, 5.1nm for Y coma, 9.9nm for 0° astigmatism and 10nm for 45° astigmatism, close to what is observed.

However, our model tells us that such a tilt of the M1 produces 0.25mm of image shift on HRC, corresponding to a target motion of 12 detector pixels. This is not seen in actual data, despite our ability to determine locations of targets on the HRC detector with sub-pixel precision. Thus, we can conclude that these physically plausible motions of mirrors can't be the cause of the variations of coma and astigmatism over an orbit.

If the exercise is performed of simply identifying a solution which matches all the observables, without consideration of physical likelihood, but with preference given to those combinations offering the least movement per element, then an interesting solution involves only the HRC's M1 and AM elements as described: M1 decenters $10\mu\text{m}$ in X and $10\mu\text{m}$ in Y; AM decenters opposite amounts, distorts its X parameter by 5×10^{-7} (0.1%), and rotates 1.3° ("Z Tilt" in Table 1). This can reproduce the right amounts of coma, astigmatism, *and* position stability observed. This solution also has the benefit of keeping the perturbations below the $15\mu\text{m}$ level believed to be reasonable. However, given the kinematic mounting which isolates the optical bench in ACS, and the actively controlled stable temperatures within the instrument, it is difficult to understand how such motions can occur.

6. Summary

Using nothing more than interpolations from Table 1 and the properties of linear combinations, determining combinations of our three elements plus the various perturbations that can produce given total amounts of coma astigmatism becomes nearly a matter of simple inspection and addition.

It was found that none of the three relevant optical elements alone can explain the observed coma and astigmatism. Furthermore, combinations of elements and perturbations can describe observed coma and astigmatism but most of these also predict an obvious amount of image motion (at the HRC or HST focal plane), which is not observed. The family of solutions that are more consistent with all the observables, including image stability, are seen to require physical perturbations so large as to be highly implausible.

The Phase Retrieval algorithm determines aberrations solely from the shape of the PSF, and characterizes PSF morphology only in terms of those Zernike coefficients that are fitted: (e.g. wavefront tip/tilt, focus, coma, and astigmatism) and those that are fixed. This means that a change in the shape of the PSF not caused by an optical aberration will be attributed to such nonetheless. We have seen that evolution in detector CTE in WFPC2/PC is interpreted as Y coma change by Phase Retrieval, and while HRC images have no such obvious effect, the issue of non-optical detector effects influencing aberrations analyses is a logical and important area to be investigated further, given the negative results attempting to correlate the observations with optical misalignments.

7. Appendix

7.1 Distortion

As part of our Zemax simulations, we also looked at field distortion induced at ACS/HRC by our perturbations.

First, in the same way that we checked the Zemax aberration results against the well-determined case of focus in Section 3.1.6, we established confidence that the Zemax scale agrees with an independently-determined value by comparing its mean plate scale for HRC (given our believed current HST+HRC optical alignment, Hartig 2002) with the value established by multiple methods and reported in the ACS Instrument Handbook. The modeled value of $0.0283''/X_{\text{pixel}} \& 0.0252''/Y_{\text{pixel}}$ is equal to the Handbook value of $0.028'' \times 0.025''$ within the significant digits' precision.

The main cause of ACS distortion is the fact that the CCD detector is not perpendicular to the optical axis. What is the amount of field distortion induced at HRC resulting from our misaligning and distorting of optical elements? We modeled a $20'' \times 20''$ grid on the sky and simulated despace, decenter, and tilts of the OTA SM to explore how these motions affect the plate scale. Despace proved to be the main cause of plate scale change but $10\mu\text{m}$ despace of the SM would change the mean scale only by 0.003%, with most of this along the detector X axis. In addition,

we found that a despace by 10 μ m or a tilt by 0.01° would change the angle between the non-orthogonal detector axes by 5".

8. References

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