

Focus History of the *Hubble Space Telescope*—Launch to May 1993¹

H. HASAN

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland 21218
 Electronic mail: hasan@stsci.edu

C. J. BURROWS

Space Telescope Science Institute and European Space Agency, 3700 San Martin Drive, Baltimore, Maryland 21218
 Electronic mail: burrows@stsci.edu

D. J. SCHROEDER

Beloit College, Department of Physics, Beloit, Wisconsin 53511
 Electronic mail: schroeder@beloit.edu

Received 1993 June 6; accepted 1993 July 22

ABSTRACT. Since the launch of the *Hubble Space Telescope* (*HST*) the secondary mirror of the telescope has been moved several times in order to collimate the telescope and also to define a position of best focus. In addition to these moves the focus position changes over time because of water desorption by the graphite epoxy in the metering truss. We report here the focus history of the telescope based on a knowledge of the mirror moves made and an analysis of desorption monitoring data obtained by the faint object camera (FOC) in the $f/96$ mode and of the routine calibration data obtained by the Wide Field and Planetary Cameras. Focus values were extracted using two different methods. In the first method the distance between the center of the point-spread function (PSF) and the shadows of the pads supporting the *HST* primary mirror are related to the focus error. In the second method an analytical formula for the PSF with variable aberration coefficients is fitted to the data. Focus positions derived from the two methods show good agreement. The data show that a desorption of about $83\ \mu\text{m}$ has taken place since 1990 August 16. The desorption has not leveled off as expected from the trend of the earlier data. Long-term variations of the secondary-mirror position of $\sim 3\text{--}15\ \mu\text{m}$ from the “best” focus position have been observed. Variations of the order of $2\text{--}5\ \mu\text{m}$ over an orbital period have also been noted. Focus changes resulting from secondary-mirror movements greater than $\sim 5\ \mu\text{m}$ change the point-spread function significantly and make deconvolution and quantitative measurements difficult.

1. INTRODUCTION

The Optical Telescope Assembly (OTA) in the *Hubble Space Telescope* (*HST*) consists of a 2.4-m aperture $f/24$ Ritchey–Chrétien telescope. It is now well established that the telescope suffers from spherical aberration and that no choice of focal plane yields the diffraction-limited images that the telescope was designed to produce. Since the spherical aberration in the *HST* primary mirror causes different parts of the beam to converge at different points, there is no well-defined focal point. Nevertheless, criteria can be set up to determine a “best” focus position for the telescope. Maintenance of the focus of the telescope is important for the present state of *HST*, since departures of more than $\sim 5\ \mu\text{m}$ (corresponding to $\sim 1/20$ th of the wave of focus error at $6328\ \text{\AA}$) change the point-spread function (PSF) significantly and make deconvolution and quantitative measurements difficult.

In 1991 April a panel of optics experts (Optical Alignment Panel) was set up by the Project and was assigned the

task of identifying a suitable focus position for the telescope. The definition of “best” or “optimal” focus initially adopted was that position of the OTA secondary mirror that gives the maximum encircled energy in a 0.1 arcsec radius of a stellar image in the Faint Object Camera (FOC) (at the internal FOC focus position at launch) at $4860\ \text{\AA}$ (Schroeder 1991). From simulations, this secondary mirror position corresponds to a shift in the focal plane from paraxial focus of 12.2 mm (paraxial focus is nominally at 1500.128 mm from the OTA primary mirror). This position is a compromise for the cameras [Wide Field and Planetary Camera (WF/PC) and FOC] and the spectrographs (Faint Object Spectrograph and Goddard High-Resolution Spectrograph), for which we know from simulations that the throughput in the small apertures is greater for positions of the secondary mirror closer to the primary mirror than the “best focus” position.

In order to establish the best focus and to put the mirror at this position, on 1991 October 18, a series of FOC $f/96$ images were taken at various positions of the secondary mirror (“focus sweep”). The OTA secondary-mirror position as determined by these data was about $5\ \mu\text{m}$ too close to the primary mirror (Jedrzejewski 1991). As this position is very close to the nominal best focus and con-

¹Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA Contract No. NAS5-26555.

siderable calibration data had already been obtained at this focus setting, it was subsequently decided to maintain the OTA focus at this position. In order to avoid frequent moves of the secondary mirror, our present aim is to maintain the telescope focus to within 0.55 mm of this position or equivalently a motion of 5 μm of the secondary mirror. In the past this goal has not been achieved. However, we are able to reconstruct the average focus history to the desired accuracy *post facto*. The relationship between a move $\Delta(\text{PF})$ of the focal plane to the corresponding move $\Delta(\text{SM})$ of the secondary mirror, in the same coordinate system, is computed from the standard relation for a Cassegrain system (Schroeder 1987):

$$\Delta(\text{PF}) = (m^2 + 1)\Delta(\text{SM}) = 110\Delta(\text{SM}), \quad (1)$$

where $m = f/f_1 = 24/2.3 = 10.435$ is the magnification of the secondary mirror. Here f and f_1 are the f numbers of the OTA and the primary mirror, respectively.

The focus position changes over time because of water desorption of the graphite epoxy in the metering truss that causes the secondary mirror to move. In addition, a 2–5 μm movement of the secondary over short periods of time has been observed in both FOC and WF/PC images. The cause for this change, commonly referred to as OTA “breathing,” is not understood. One case of “heavy breathing” in which a secondary-mirror movement of $\sim 10 \mu\text{m}$ between a WF and a PC exposure taken ~ 2.5 hr apart has also been detected.

An observatory level test (OLT) to monitor desorption was devised during the science verification (SV) phase of *HST* and has been periodically executed since then (the interval between tests at present is twelve weeks). Analysis of these data through 1993 January showed that the OTA had desorbed a total of about 83 μm , but at a decreasing rate, since 1990 August 16. A best-fit curve through the data indicates that the OTA will shrink another $\sim 8 \mu\text{m}$ by 1993 August. The secondary is moved back to a position within 5 μm of the 1991 October 18 focus position to correct for the desorption. In order to minimize the secondary-mirror moves, the plan is to apply an overcorrection so that further desorption will cause the mirror to move toward the desired focus position. The last mirror move to correct for desorption was made on 1992 November 25. If the desorption continues along the present trending curve another move will not be required until 1993 August.

Here we report the results of the FOC $f/96$ desorption test as well as results of monthly focus measurements on WF and PC images taken from the stellar-monitoring program. Although the WF and PC data are of a poorer quality than the FOC data, both because the signal to noise is lower and because these images are undersampled, they have been analyzed to provide trending information since 1991 September.

The history of OTA secondary-mirror actuator movements is available on the Space Telescope Electronic Information Service (STEIS) in the directory software/TIM. A table of the major mirror moves affecting scientific observations is given in Sec. 2.

TABLE 1
All Scientifically Relevant OTA Secondary-Mirror
Moves Since Launch

Yr	Day	Date/Time (GMT)	Secondary Position					
			DX	DY	DZ	TX	TY	TZ
			+V1	+V3	+V2	−OV1	+OV2	−OV3
			μm	μm	μm	arcseconds		
90	114	LAUNCH	0	0	0	0	0	0
90	140	20-May-90 08:20	−615	0	0	0	0	0
90	166	15-Jun-90 10:50	−690	−392	152	0	−212	133
90	176	25-Jun-90 21:36	−539	0	0	−1	0	0
90	204	23-Jul-90 07:42	−711	−129	304	0	−86	61
90	227	15-Aug-90 18:09	−701	−377	537	1	−170	140
90	299	26-Oct-90 15:08	−681	−377	537	1	−170	140
90	351	17-Dec-90 01:36	−680	−109	281	1	−79	53
91	053	22-Feb-91 14:50	−655	−109	281	1	−79	53
91	081	22-Mar-91 14:06	−655	153	19	1	−79	53
91	096	06-Apr-91 22:22	−655	−109	281	1	−79	53
91	101	11-Apr-91 22:26	−640	−109	281	1	−79	53
92	236	23-Aug-92 23:37	−626	−109	281	1	−79	53
92	330	25-Nov-92 12:46	−616	−109	281	1	−79	53

2. MIRROR MOVE HISTORY

There have been a total of 215 mirror adjustments since launch, mainly for engineering purposes. The 13 moves affecting scientific observations are listed in Table 1. The last six columns of the table give the secondary-mirror position relative to the launch position, in physical units (microns of translation and arcseconds of tilt). The OTA coordinate system ($V1$, $V3$, $V2$) is used here. The $V1$ axis is along the *HST* optical axis, and together with the ($V2$, $V3$) axes forms a right-handed system with the focal plane lying in the ($V2$, $V3$) plane. Translations (DX , DY , DZ) are along the ($V1$, $V3$, $V2$) axes, respectively, while the tilts (TX , TY , TZ) are about ($−V1$, $+V2$, $−V3$), respectively. The effect of desorption, which is estimated from the results of the focus test, is not included in Table 1. The telescope has been routinely maintained at the same collimation (secondary-mirror tilt and decenter) since day 351 in 1990, with only focus variations ever since. This collimation setting was first used on day 323 in 1990 and is, therefore, generally known as the “day 323” position. The only exceptions are the period between days 81 and 96 in 1991 and periods in which alignment testing was being done and no science data was taken. After each collimation excursion, the secondary mirror was repositioned to high accuracy at the “day 323” position. The “day 323” position is known to have some misalignment associated with it corresponding to about 1/15th waves of coma at 6328 Å.

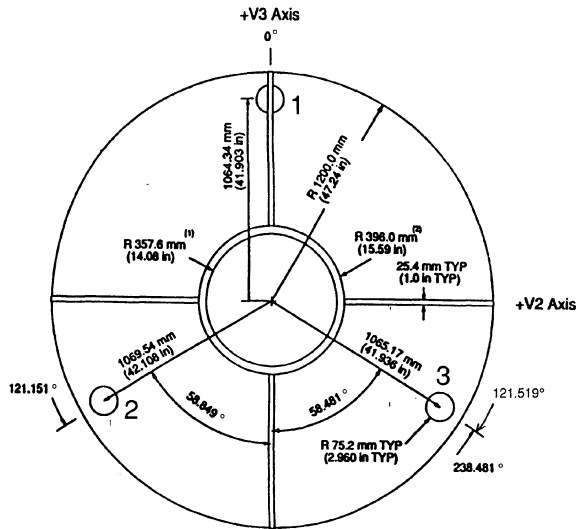


FIG. 1—OTA exit pupil used for constructing model PSFs. The outermost circle represents the OTA primary mirror; the inner circle represents the central obscuration caused by the baffle supporting the OTA secondary mirror. The three small circles labeled 1, 2, and 3 are obscurations caused by the pads supporting the primary mirror. The four rectangular obscurations are caused by the spiders supporting the OTA secondary. The OTA axes (V_2 , V_3) are shown.

This coma will be removed with a secondary-mirror move after the servicing mission scheduled for 1993 December.

3. METHOD OF ANALYSIS

Initially, two methods were used to measure the focus position of the OTA—the “pad method” developed by Schroeder (1991) and “phase retrieval.” Both methods showed good agreement and are outlined below, although the pad method is used for routine analysis because of its simplicity.

3.1 Pad Method

The “pad method” is based on the observation that the diffraction shadows of the three pads supporting the OTA primary mirror (PM) (Fig. 1) are clearly seen in any well-exposed stellar image. These pad images, seen as “bright spots,” are the so-called Arago or Poisson spot seen behind any circular obstacle. The method consists simply of displaying the image, measuring the distance r from the center of each spot to the image peak, and using the average $\langle r \rangle$ to find the distance $\Delta(\text{PF})$ from paraxial focus to the focal surface of the OTA. The spot centers are measured in detector coordinates and then converted to OTA distances using the known scale factor for the camera.

The distance between the pad images varies with focus, as shown schematically in Fig. 2. The relation between $\langle r \rangle$ and $\Delta(\text{PF})$ or, the corresponding shift $\Delta(\text{SM})$ of the secondary mirror (SM) from its nominal position, is most easily derived by ray tracing. Other optical changes such as those in the radius of curvature of the primary mirror can

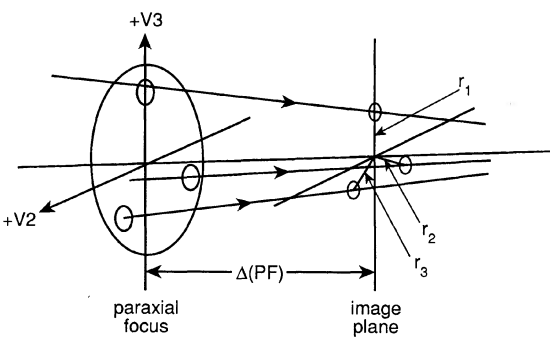


FIG. 2—A schematic diagram showing the relation between the pupil image at paraxial focus and at a distance $\Delta(\text{PF})$ from a paraxial focus. Rays through the centers of the three pads are shown proceeding from paraxial focus to the image plane. The pad radii measured on the image are denoted by r_1 , r_2 , r_3 .

lead to focus changes. There is no practical way to distinguish the cause of a focus shift. In this approach we take the as-built OTA and trace rays from the centers of the pads on the PM to the image surface for several SM positions. The traces are done for a star on the OTA axis, hence only spherical aberration (SA) and defocus determine $\langle r \rangle$. Our assumption is that each pad spot in an image is centered on the geometric ray through the corresponding pad center.

The average position of rays traced through the pad is displaced by $2.8 \mu\text{m}$ from the ray at the pad center, which corresponds to only $1.4 \mu\text{m}$ of OTA secondary-mirror motion. The as-built parameters of the OTA are as follows: PM: radius of curvature = 11041.7 mm, conic constant $K = -1.0139$, distance to SM = 4906.889 mm; SM: radius of curvature = 1358.065 mm, conic constant $K = -1.496$, distance from PM vertex to focal surface = 1500.128 mm. The PM–SM separation above corresponds to $\Delta(\text{PF}) = \Delta(\text{SM}) = 0$. Taking the coordinates of the pad centers from Fig. 1, we get the results in Table 2.

The positive displacements $\Delta(\text{SM})$ in this table are away from the PM. Positive $\Delta(\text{SM})$ decreases the PM to the paraxial focus distance. On the OTA instrumental aperture plane, which is fixed relative to the primary mirror, positive $\Delta(\text{SM})$, therefore, corresponds to an image closer to marginal focus.

TABLE 2
Average Pad Circle Radius $\langle r \rangle$ vs. $\Delta(\text{SM})$

$\Delta(\text{SM})$	$\langle r \rangle$	$\Delta(\text{PF})$	$\langle r \rangle$
μm	μm	mm	FOC pixels
0	596.5	0	87.57
100	396.8	10.97	58.25
200	197.0	21.92	28.92

Using the data in the two left columns in Table 2, we get the following relation between $\langle r \rangle$ and $\Delta(\text{SM})$:

$$\langle r \rangle (\text{microns}) = 596.5 - 1.998\Delta(\text{SM}) (\text{microns}). \quad (2)$$

A conversion from $\langle r \rangle$ in microns to $\langle r \rangle$ in pixels can be made by using the camera scale projected on the $f/24$ focal plane as follows. From the OTA scale of $3.581 \text{ milliarcsec } \mu\text{m}^{-1}$ and the FOC $f/96$ scale of $24.4 \text{ milliarcsec pixel}^{-1}$, we get a conversion factor of $6.812 \mu\text{m FOC}^{-1} \text{ pixel}$ at the $f/24$ OTA focus. (N.B. The geometric correction algorithm applied by the pipeline when processing early FOC $f/96$ data gave a scale of $24.4 \text{ milliarcsec pixel}^{-1}$ rather than $22 \text{ milliarcsec pixel}^{-1}$. We continue to process our data in the same way in order to maintain consistency between measurements.) When this conversion factor is applied to Eq. (2) we get

$$\langle r \rangle (\text{pixels}) = 87.57 - 0.2933\Delta(\text{SM}) (\text{microns}). \quad (3)$$

The corresponding conversion factors for PC and WFC are based on scales of 43 and 100 milliarcsec pixel $^{-1}$ and give the equations, respectively:

$$\langle r \rangle (\text{pixels}) = 49.7 - 0.1665\Delta(\text{SM}) (\text{microns}), \quad (4)$$

$$\langle r \rangle (\text{pixels}) = 21.4 - 0.0716\Delta(\text{SM}) (\text{microns}). \quad (5)$$

The results in Table 2 can also be derived by another approach. The transverse spherical aberration (TSA) is computed as the product of the OTA focal length and the change in slope of the nominal optical path difference (OPD) between an aberrated ray and the chief ray (the ray that goes through the optical center of the system). The difference between TSA and pad radius $\langle r \rangle$ is then related to $\Delta(\text{SM})$ by simple geometric means (Burrows et al. 1991). Ray tracing is preferred, however, for two reasons. First, the SA of the as-built OTA depends on the PM-SM separation; over the range of SM displacement in the table there is a change of about 1% in third-order SA. Second, the as-built OTA has a residual fifth-order SA not present in the OTA as designed. These two factors are automatically accounted for when rays are traced, but must be explicitly included if the OPD approach is used, although ray trace shows them to be small. A comparison of results obtained using Eq. (3) and the corresponding equation using the OPD approach are shown in columns 2 and 3 of Table 3.

3.2 Phase Retrieval Method

In this method a theoretical model of the PSF is fitted to the data. The theoretical model and fitting procedure are described below.

3.2.1 Theoretical PSF Model

The optical path difference between a particular ray and the chief ray (the ray that goes through the optical center of the system) may be expressed in terms of polynomials. An appropriate set of polynomials used for this purpose was developed, for a circular aperture with a centered circular obscuration, by Zernike (1934). Each term of the

TABLE 3
Comparison of $\Delta(\text{SM})$ Using Pad Method and
Phase Retrieval Method

True	OPD	Ray Trace	Ray Trace	Phase Retrieval
	(HH)	(HH)	(DJS)	
105.9	111.7	113.4		104.7
100.9	108.1	109.6		100.4
	123.7	125.2	123	117.5
	111.6	112.6	114	107.7
	105.3	106.1	110	95.4

polynomial represents a particular optical distortion (Seidel aberration) of the system. The expansion coefficients give the “strength” of the aberration. Thus, for an unaberrated beam all the coefficients will be zero. The OPD or wave front error, $F(r, \theta)$, at any point (r, θ) may be expanded in terms of Zernike polynomials, $Z_i(r, \theta)$ as (Born and Wolf 1965)

$$F(r, \theta) = \sum_{i=1}^{N_{\max}} a_i Z_i(r, \theta). \quad (6)$$

From Fourier optics, spread of light at the image is determined both by the wave front error and the geometry of the beam in the exit pupil. The amplitude spread function (ASF), which quantifies this light distribution mathematically, is the Fourier transform of the pupil function $P(r, \theta)$, given by

$$P(r, \theta) = A(r) O(r, \theta + \omega) e^{ikF(r, \theta)}, \quad (7)$$

where λ is the wavelength of light, $k = 2\pi/\lambda$ is the wave number, and $O(r, \theta + \omega)$ takes into account the obscuration of the light beam. The angle ω gives an overall rotation of the obscurations with respect to detector coordinates. For the OTA, in addition to the central obscuration, the beam has obscurations caused by the spider supports of the secondary-mirror and the primary-mirror pads (Fig. 1).

The PSF is determined as the modulus squared of the ASF. Effects of low-order aberrations caused by irregularities in the OTA primary-mirror surface and *HST* jitter may be modeled by modifying $F(r, \theta)$ and the ASF, respectively.

3.2.2 Fitting Procedure

We minimize a merit function which is the rms difference between a simulated and observed PSF, using a non-linear fitting routine CURFIT (Bevington 1969) by varying the coefficients for focus and spherical aberration. This method allows an independent estimate of spherical aberration and focus, unlike the pad method which gives focus for an assumed amount of spherical aberration.

The aberration coefficient Z_4 corresponds to a focus error which can be shown by geometric arguments to correspond to a SM displacement, $\Delta(\text{SM})$ by

$$\Delta(\text{SM}) = (Z_4^c - Z_4^p) (3.887 \times 8F^2) / 110, \quad (8)$$

where $\Delta(\text{SM})$ is expressed in microns as before, Z_4^c and Z_4^p are the focus error at the focus position being measured and paraxial focus, respectively, $F = 24 \times 0.9984$ is the actual OTA image space focal ratio at paraxial focus. At paraxial focus the wave front error is proportional to r^4 . Thus Z_4^p may be easily computed by equating the r^2 term in the orthogonal expansion of spherical aberration to the r^2 term from the focus polynomial with coefficient Z_4 . For the OTA we get $Z_4^p = -1.249 \mu\text{m}$.

3.3 Comparison of Pad Method and Phase Retrieval Method

A comparison of the values for $\Delta(\text{SM})$ obtained by the pad method and the phase retrieval method for some representative FOC $f/96$ images are shown in Table 3. The first two lines of this table show the results for images, which were simulated for $\Delta(\text{SM}) = 105.9 \mu\text{m}$ and $\Delta(\text{SM}) = 100.9 \mu\text{m}$, respectively, while the last three lines give results for observed images. Columns 2 and 3 show the results obtained using the OPD method and Eq. (3), respectively, of measurements of pad positions made by one of us (H.H.). Column 4 shows the same measurements made by another of us (D.J.S.) and uses Eq. (3). Finally, column 5 shows the results of the phase retrieval method.

Both the pad method and the phase retrieval method give good agreement in measuring relative focus changes. The difference in the absolute value of $\Delta(\text{SM})$ between the two methods is $\sim 7 \mu\text{m}$; the phase retrieval method gives a consistently smaller value. This constant bias is due to the fact that the pad method relies on the judgement of the human eye to centroid the pad image. For this reason an interpersonal bias appears as is evident when comparing results measured by two different people (columns 3 and 4). The reproducibilities of $\Delta(\text{SM})$ caused by variations in repeated measurements of the pad centers in a single FOC image is $\pm 3 \mu\text{m}$. The phase retrieval method is generally more reliable and bias free. However, when the image has a great deal of jitter (as was the case in image 3 of Table 3), the phase retrieval method does not converge to a very good value. A sanity check on either method is to blink successive images to estimate focus changes. To an experienced eye, gross errors become very apparent. For the phase retrieval method, blinking the data and fitted image also gives a good estimate of whether the method has converged well or not.

4. RESULTS

4.1 Analysis of FOC Data

The FOC desorption monitoring test is four 15-min images of the spectrophotometric standard star Grw+70°5824 through the filter F486N using the FOC $F/96$. The four images are coadded to improve the signal-to-noise ratio. The data were analyzed by the pad method

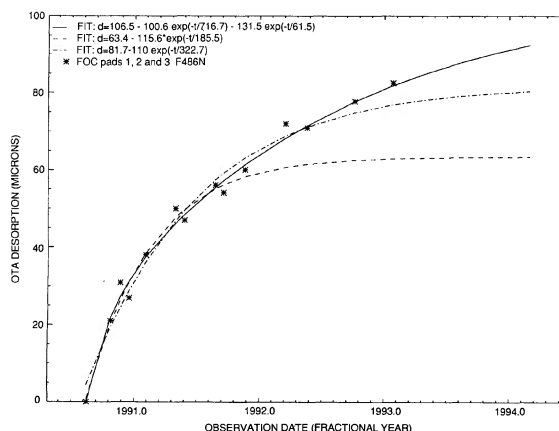


FIG. 3—Desorption measurements and the best-fit curves for FOC data available until 1991 November 20 (dashed curve), 1992 May 19 (dot-dash curve), and current best fit (solid curve). There is a large difference between the curves beyond 1991 November 20.

and are plotted together with fits in Fig. 3. Initial fits to the available data (until 1991 November 20) indicated that the OTA was desorbing according to the formula

$$d = 63.4 - 115.6e^{-t/185.5}, \quad (9)$$

where d is the desorption in microns since 1990 August 16 and t is the number of days since 1990 April 24 (*HST* launch). Subsequent data did not follow this curve and another fit was done (data until 1992 May 19) leading to the formula

$$d = 81.7 - 110.0e^{-t/322.7}. \quad (10)$$

The test done on 1992 October 6 indicated that this formula was still not good enough to predict the OTA desorption. The last fit gave the formula

$$d = 106.5 - 100.6e^{-t/716.7} - 131.5e^{-t/61.5}. \quad (11)$$

Figure 3 shows a plot of the measurements and the best fit curves for data available until 1991 November 20 (dashed curve), 1992 May 19 (dot-dashed curve), and 1992 October 6 (dotted curve). There is a large difference between the curves beyond 1991 November 20. The desorption has not leveled off as suggested by the first fitted curve with the smallest time constant. Results of the latest desorption test on 1993 January 26 indicate that the desorption continues along the last fitted curve.

A mirror move of $14 \mu\text{m}$ to counter desorption was made on 1992 August 23. This move, which was based on a fit to the data available through 1992 May 19 (dot-dashed curve in Fig. 3), fell $\sim 3 \mu\text{m}$ short of the 1991 October 18 position. Another move of $10 \mu\text{m}$ was made on 1992 November 25 to overcorrect the focus by $\sim 3 \mu\text{m}$. Desorption will cause the focus to slowly drift to the 1991 October 18 position without frequent mirror moves.

Figures 6 and 7 show the reference positions for 1991 October 18 as well as the moves made to counter desorption. Table 4 lists the dates of the desorption tests and results of the measurements.

TABLE 4
Desorption of Secondary Mirror as
Measured by the Pad Method

Date	Days since launch	Microns measured
16-Aug-90	114	0.0
24-Oct-90	183	21.0
21-Nov-90	211	31.0
17-Dec-90	237	27.0
2-Feb-91	284	38.0
30-Apr-91	371	50.0
26-May-91	397	47.0
24-Aug-91	487	56.0
17-Sep-91	511	54.0
20-Nov-91	575	60.0
17-Mar-92	693	72.0
19-May-92	756	70.9
6-Oct-92	896	77.7
26-Jan-93	1008	82.5

4.2 Analysis of PC Data

Data from the PC stellar monitoring proposals were analyzed for the period 1991 September 13 through 1993 May 15. In this test a standard star was exposed for 1.2 s on chip PC6, using a series of filters. The images most suitable for focus analysis were the ones through the F439W filter because in this bandpass the pad images are clearest. It should be mentioned that these are not very well-exposed images so the pad positions are not easy to measure. Because of this and of the undersampling of WF/PC images the uncertainties are larger than in the case of the FOC data. The images were displayed and the positions of pads 2 and 3 measured. Pad 1 was not clearly visible in most images as it falls in the shadow of the OTA spider in PC6. The uncertainties in its measurements are expected to be larger than in the other two cases. Values of $\Delta(\text{SM})$ were computed from Eq. (4) and are overplotted with the FOC data in Fig. 4 after adjusting for an apparent focus difference of $\sim 8 \mu\text{m}$ between the FOC and PC. In each case, five measurements were made for each image from which the 1σ values were computed and plotted as error bars. These data are also overplotted with the FOC data in Fig. 6 together with the mirror moves made to counter desorption.

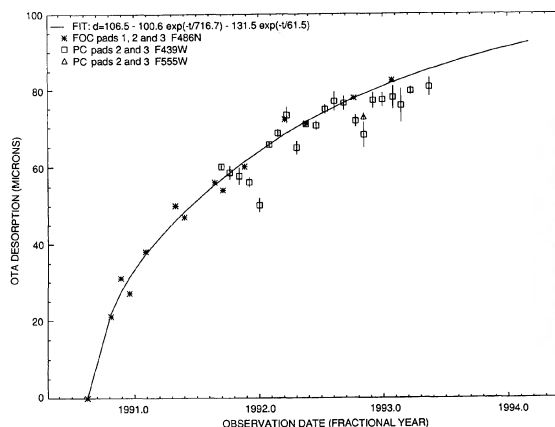


FIG. 4—Desorption measurements from PC observations through filter F439W overplotted with measurements from FOC data through filter 486N. The best-fit curve, the equation for which is given at the top of the diagram, is plotted as a solid line. Because of the large discrepancy seen between the WF and PC data on 1992 November 4, PC data through filter F555W were analyzed and are also plotted.

There is a great deal of scatter in the data but they do follow the general trend of the FOC data.

4.3 Analysis of WF Data

The WF data were taken from the same proposals as the PC data above and analyzed as described in Sec. 4.2. The exposures were 0.6 s on chip W2. Only the positions of pads 2 and 3 were measured, since pad 1 was barely visible. The results are overplotted with the FOC data in Figs. 5 and 7 with an arbitrary normalization. There is a global shift of $\sim 6 \mu\text{m}$ (or $\sim 1/20$ th wave of focus error at $6328 \text{ \AA}$) between the normalization of the WF and PC data. Similar offsets in focus between the WF and PC cameras in

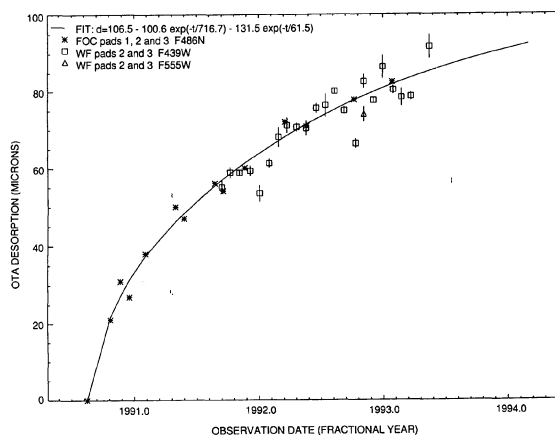


FIG. 5—Desorption measurements from WF observations through filter F439W overplotted with measurements from FOC data through filter 486N. The best-fit curve, the equation for which is given at the top of the diagram, is plotted as a solid line. Because of the large discrepancy seen between the WF and PC data on 1992 November 4, WF data through filter F555W were analyzed and are also plotted.

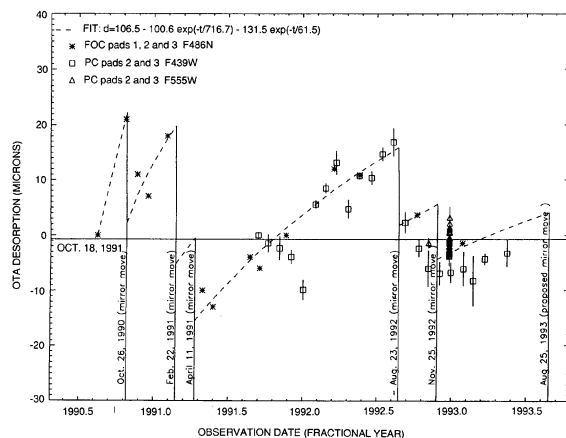


FIG. 6—Reference position for 1991 October 18 as well as the mirror moves made to counter desorption are indicated on the plot. The FOC and PC data are overplotted together with the desorption curve (dashed lines). Also overplotted here are the results of measurements on the 34 images taken in the CVZ through filter F555W on 1992 December 25. In the past, large excursions from the 1991 October 18 position have occurred. When choosing PSFs for deconvolution the focus changes on a time scale of months should be taken into account.

WF/PC2 have been seen in global tests. The WF data also follow the general trend of the FOC and PC data.

5. OTA “BREATHING”

Each set of FOC data contains several exposures, and the focus measurements reported above were made on the sum of the exposures. However, within some sets is shown 2–5 μm of focus variation which are not attributable to measurement errors. This short-period variability is referred to as OTA “breathing.” Such focus variations on an orbital time scale have also been seen in WF and PC data.

A test designed to measure focus changes on an orbital scale was executed on 1992 December 25. In this test, 34 images were taken in PC5 over six *HST* orbits with the

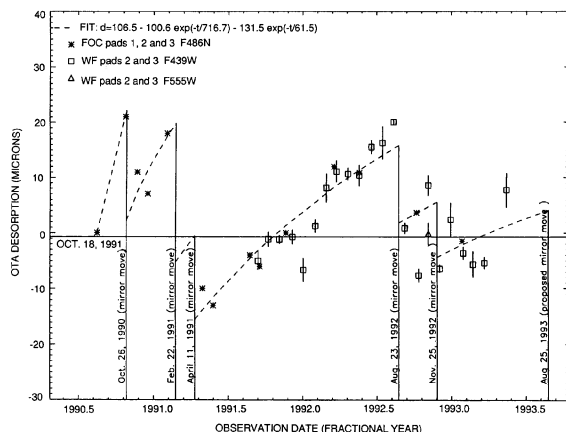


FIG. 7—Reference position for 1991 October 18 as well as the mirror moves made to counter desorption are indicated on the plot. The FOC and WF data are overplotted together with the desorption curve (dashed lines).

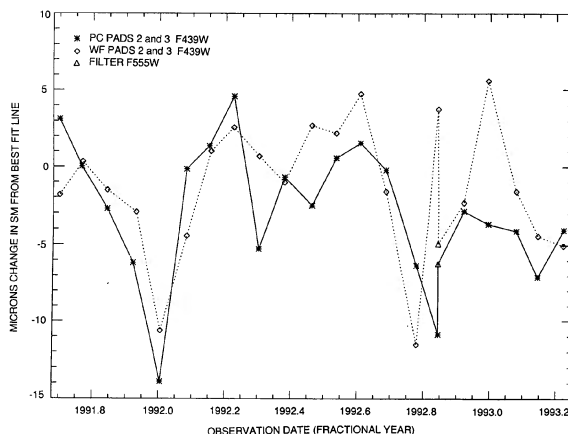


FIG. 8—Differences in $\Delta(\text{SM})$ obtained from measurements and the best-fit (desorption) curve for WF/PC stellar-monitoring data.

target in the Continuous Viewing Zone (CVZ). Results of the pad measurements on these images are plotted in Fig. 9 and indicate $\sim 3 \mu\text{m}$ focus changes [in terms of $\Delta(\text{SM})$ movement] between most of the images with the largest departure being $\sim 7 \mu\text{m}$ (blinking the images indicates that the largest error is $\sim 5 \mu\text{m}$). The breathing appears to be erratic and the cause is not yet known, although there is some indication that orbital variations of the focus may be thermally induced.

Over periods of months, the WF/PC stellar-monitoring data (Figs. 4 and 5) show significant and larger departures from the best-fit line as plotted in Fig. 8. There is generally good correlation between the PC and WF residuals. (One anomalous case exists on 1992 November 4 when a difference of $\sim 10 \mu\text{m}$ was found between the PC and WF data.)

Departures from the best-fit line plotted in Fig. 8 show long-term focus variations of $\sim 3\text{--}15 \mu\text{m}$. Since the WF and PC data are well correlated, and the amplitude is larger than that associated with the orbital breathing, this large range of focus variations is probably caused by a

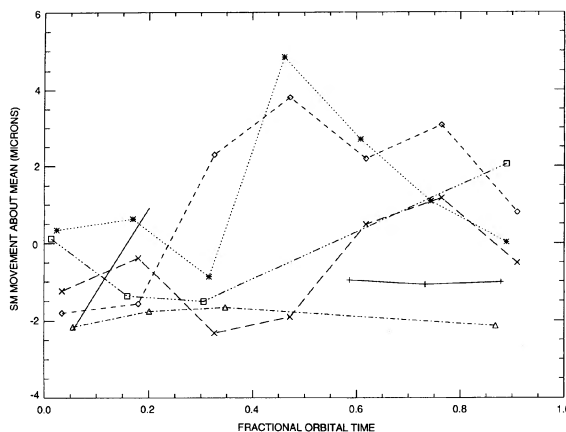


FIG. 9—Variation of $\Delta(\text{SM})$ over five complete orbital cycles and two partial cycles. The measurements for each cycle are denoted by a different symbol and connected by different line styles. The lines are a guide to the eye.

focus offset (about which breathing may occur) which is dependent on the Sun–Earth–*HST*–target geometry.

The picture that emerges from these results is that there is a short-term (over an orbital period) focus variation of $\sim 3\text{--}5\ \mu\text{m}$ (although occasionally a bigger effect has been seen), and a larger one of $\sim 3\text{--}15\ \mu\text{m}$ which may be pointing dependent. From simulations we know that “breathing” of $3\text{--}5\ \mu\text{m}$ would not significantly degrade the WF/PC2 or COSTAR images and corresponds to at most 1/20th rms wave front error at $6328\ \text{\AA}$, and to a loss of central intensity of $\sim 5\%$ at $6328\ \text{\AA}$ and $\sim 30\%$ at $2000\ \text{\AA}$. For the spectrographs, a $5\ \mu\text{m}$ focus change does not affect the throughput for the large ($1'' \times 1''$) aperture and causes $< 1\%$ change for the small ($0''.25 \times 0''.25$) aperture. Focus variations greater than $5\ \mu\text{m}$ would have a somewhat detrimental effect on scientific observations. However, since the larger variations may be related to *HST* pointing, and relatively uncommon, they are unlikely to have a serious impact on an individual scientific program. A better understanding of the effect must be achieved however, as it could be largely avoided by changing the *HST* scheduling after the refurbishment mission scheduled for 1993 December.

6. CONCLUSION

Analysis of the desorption data from 1990 August 16 through 1993 January 26 shows that the OTA has desorbed $\sim 83\ \mu\text{m}$ according to the formula

$$d = 106.5 - 100.6e^{-t/716.7} - 131.5e^{-t/61.5}, \quad (12)$$

where d is the desorption in microns since 1990 August 16 and t is the number of days since 1990 April 24 (*HST* launch). If the desorption continues along the present curve, focus will be maintained within $3\ \mu\text{m}$ of the 1991 October 18 until the next move planned in 1993 August.

The dominant source of OTA focus variations since the 1992 November mirror move is OTA “breathing.” The period between 1991 April and 1992 August has seen larger focus variations (on the time scale of several months differences in focus corresponding to secondary-mirror positions which differ by $10\text{--}20\ \mu\text{m}$) owing to OTA desorption. For deconvolution, observers should choose PSFs judiciously. If observed PSFs are chosen for deconvolution, Fig. 6 can be used as a guideline to ensure that the PSF was taken at a date when the secondary mirror was within $5\text{--}10\ \mu\text{m}$ of its position on the date that the data being deconvolved was taken. Simulated PSFs generated for deconvolution purposes should be computed at the best-fit focus position on the date of the observation, as is done by the Telescope Image Modeling (TIM) software (Burrows et al. 1990) developed at the Space Telescope Science Institute, but may need additional focus corrections of $5\text{--}10\ \mu\text{m}$.

We would like to thank Ralph Bohlin and the referee for reviewing the manuscript and making useful suggestions.

REFERENCES

- Bevington, R. P. 1969, *Data Reduction and Error Analysis for the Physical Sciences* (New York, McGraw–Hill), p. 235
- Born, M., and Wolf, E. 1965, *Principles of Optics*, 3rd ed. (Oxford, Pergamon), p. 464
- Burrows, C. J., Holtzman, J. A., Faber, S. M., Bely, P. Y., Hasan, H., Lynds, C. R., and Schroeder, D. 1991, *ApJ*, 369, L21
- Jedrzejewski, R. 1991, in *Optical Alignment Panel Final Report*, December 1991
- Schroeder, D. 1987, *Astronomical Optics* (San Diego, Academic), p. 20
- Schroeder, D. 1991, *Optical Alignment Panel Final Report*, December 1991
- Zernike, F. 1934, *Physica*, 1, 689