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Impact of Focus Drift on Aperture Photometry

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ABSTRACT

We have examined the impact of the long term and short term focus position variations on small aperture photometry. For both the WF cameras and the PC, the effect has been found to be small for aperture radii of about 5 pixel or larger. At smaller aperture radii, the magnitude corrections for defocusing become important for absolute photometry if high photometric accuracy is needed. The aperture corrections phased with the focus drift are given for the filters F439W, F555W, and F814W for the PC and the WF3 camera. They are compared with the early results in Holtzman et al (1995a). With regard to short term focus variations, we have found that, depending on the current average focus position, the aperture magnitudes may vary due to the effect of focus "breathing" by a few percent, and up to ~10% for the aperture radius r = 1 pixel. If high absolute accuracy is desired in aperture photometry, it is recommended therefore that either apertures of 5 pixels or larger be used, or the aperture correction be determined from the brightest stars in each observation. We have also found that, in the PC, the photometric zero point appears to have drifted away from its original value in a way that our primary standard looks now brighter than in April of 1994 by ~0.05 mag. In WF, the data were affected by a bug in CALWP2 and cannot be used for checking this effect until they are recalibrated. Preliminary indications, however, are that there has been a similar brightening in WF as well.

1. Introduction

Photometry of point sources in WFPC2 data is usually accomplished using one of the two methods: aperture photometry or PSF fitting. PSF fitting has two major advantages: the ability to deal with crowded conditions, by iteratively fitting and subtracting point sources, and the ability to minimize the noise in the flux measurements and the influence of the background by weighting the fitting. Properly optimized, PSF fitting is a desirable avenue for accurate photometry of faint sources.

However, PSF fitting requires good knowledge of the shape of the PSF, either a priori or from the data themselves. It is well known that the WFPC2 PSF is very difficult to characterize perfectly, being a function of position in the field of view, wavelength, and also of focus position. PSF fitting is made more complex by the undersampling of both the PC and the WF cameras, which necessitates careful handling of the subpixel centering for the model PSF. Specialized software, such as the DOPHOT package and the DAOPHOT routines, can deal with these difficulties and produce accurate photometry if enough well-exposed stars are available. If not, the resulting photometry can have slight zero-point errors due to an imperfectly known PSF. Note that in principle PSF fitting is optimal with respect to maximum signal-to-noise extraction.

Aperture photometry is a much simpler procedure which is commonly employed by many astronomers. It is much less sensitive than PSF fitting to PSF variations and pixel-centering problems, and can produce good results for well-exposed images. The size of the aperture used should be large enough to reduce any edge effects due to centering and PSF variations, but not so large as to include an undue amount of background signal, which will increase the shot noise and produce additional uncertainty if the background estimate is uncertain. Of course, the zero point of aperture photometry depends on the aperture used; the published zero points of Holtzman et al. (1995b) and Whitmore (1995) refer to an aperture radius r of 0.5 arcsec.

However, there are a number of situations in which this aperture is impractical, and smaller apertures need to be used, with the consequent need for aperture corrections. Here are a few examples:

- *Photometry of crowded stellar fields.* The light from a star in a large aperture may be directly contaminated by the light from neighboring stars in the wings of the PSF. Also the sky background, being measured from an even larger aperture, would be impacted to a great extent by the background light of unevenly distributed nearby stars. Thus the resulting magnitudes and colors will be compromised. Use of small apertures obviously enables one to reduce both effects.
- *Photometry of stars and globular clusters in external galaxies.* For these targets, an uneven background light of the parent galaxy is often a substantial source of errors in the sky background to be subtracted from the target flux in the aperture. Small apertures may be the last resort in this case too.
- *Photometry of faint sources, especially in the case of a background dominated noise.* The major adverse effect of large apertures in this case comes from background subtraction. The very fact of quantization of data numbers (DN), especially at GAIN = 15 e^-, can introduce significant errors into the total flux in the aperture if the aperture is large. In this case the count numbers in the peripheral pixels are small, hence errors in the background will have a large effect upon them. Since the number of such pixels goes up quadratically with increasing aperture radius, their contribution to the flux in the aperture will also rapidly go up, resulting in progressively increasing

error in the flux collected from the aperture area. Thus we are pushed again toward small apertures.

The advantages of small aperture photometry do not come for free. A number of factors are responsible for errors which go up with decreasing aperture radius. Perhaps the most important of them are focus drift and focus "breathing". So before we can comfortably use small aperture photometry, we need to examine these factors and find the ways to correct for their impact.

The HST focus position, *d*, is known to change systematically at a rate slightly less than 1 μm / month. The change is believed to be due to the OTA shrinkage induced by desorption of water in the Metering Truss (Hasan, Burrows, & Schroeder 1993, Casertano 1995). In addition to this secular drift, there are short-term focus position variations with an amplitude of ~2 μm which presumably result from temperature variation during the orbital period (Hasan & Bely 1994). The secular defocusing makes it necessary to correct the focus position by moving the secondary mirror twice a year (see Table 1). These focus moves enable us to maintain the PSF quality within limits which are satisfactory for most observational programs. However, programs which require especially accurate absolute photometry data can be substantially compromised by the amount of focus drift accumulating in between focus corrections. In this report, we analyze the impact of the focus drift on small aperture photometry and present aperture corrections phased with the secular focus change. This study is a part of the project aimed at achieving ~1% photometric accuracy with WFPC2.

Table 1. History of focus adjustments.

date	t_i (days)[a]	adjustment (μm)	d_i (μm)[b]
3/04/94	63	minor change	+1.0
6/29/94	180	5	+1.5
1/15/95	380	5	+1.5
8/28/95	604	6.5	+2.5
3/14/96	803	5.5	+3.5

a. t_i is the day number starting January 1, 1994.
b. d_i is the focus position after the secondary mirror move, assuming a position of +1.5 μm on 6/29/94 and a focus drift rate of –0.025 μm per day.

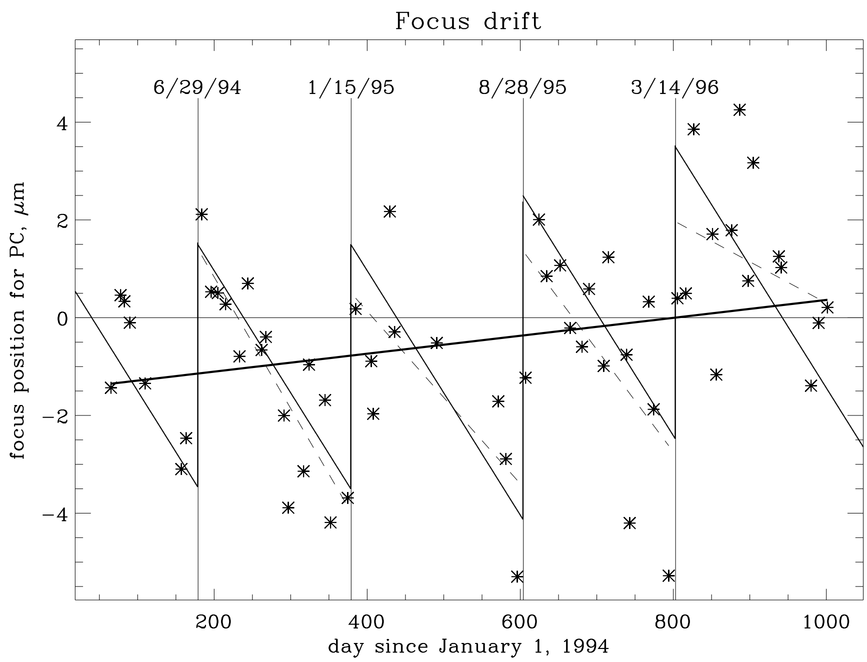
2. Focus history

The focus position monitoring based on phase retrieval solutions for the WFPC2 images of the spectrophotometric standard star GRW +70D5824 (Casertano 1995) has accumulated substantial amount of data to analyze the impact of the focus drift on photometry. The focus position measurements were done with the data obtained from exposures through the filter F555W on PC.

In this report, we will use these data to check if the measured stellar magnitudes in F555W, F439W, and F814W from the standard star images on PC and WF3 correlate with the focus drift.

Figure 1, based on analysis done together with Matt Lallo, gives a complete representation of the HST focus history after the First Servicing Mission. The focus position, d, is measured relative to the "optimal focus" which is defined as the focus position that minimizes the rms wavefront error in the PC. The slanted thin solid lines can be regarded as corresponding to the "nominal" focus position for each date covered by Figure 1. The lines have a slope of –0.025 μm/day, which translates into a focus drift rate of approximately –0.75 μm/month. The slope and the "reference point" were chosen using the values for the secondary mirror moves from Table 1 and assuming that the focus position after the focus adjustment on June 29, 1994 was at +1.5 μm. Within statistical uncertainties, the slope value does not differ from that of the regression lines calculated separately for each of the periods between the focus moves (dashed lines in Figure 1). The thick straight line is a linear regression across all focus adjustment cycles. Its slope indicates that the range of "operational" focus positions systematically changed since the First Servicing Mission from cycle to cycle. A closer inspection shows that most of the change occurred in the last two focus adjustment cycles, with the focus range substantially shifted towards more positive values.

Figure 1: Focus history. The data points are focus positions for Planetary Camera obtained from the F555W standard star images using the phase retrieval method. The zig-zag solid line indicates the actual amount of the secondary mirror move at the date of focus correction and gives the expected focus position in between the focus adjustments assuming a focus drift rate of –0.025 µm per day and a focus position of +1.5 µm after the secondary mirror move on 6/29/94. The straight thick line is the linear regression across all focus adjustment cycles.



3. Secular "brightening" of the PC magnitudes of the standard star

To derive the magnitudes of the standard star, we used the phot task from the *noao.daophot* package. The magnitudes were measured in the aperture radii of 1, 2, 3, 5, and 10 pixel. Sky subtraction was performed using an annulus of 15 pixels, with the parameter dannulus set to 5 pixels. The zeropoints were chosen on the ST photometric system, i.e., 20.220 mag, 22.553 mag, and 22.914 mag for F439W, F555W, and F814W, respectively. The data from exposures executed on April 7th, December 12th, and December 20th, 1994, were omitted because of poor quality. In particular, the last two of these observations were done with serial clocks on, which resulted in large uncertainty in the exposure time.

The measured magnitudes are plotted in Figures 2–4 as function of the date of observation. One may notice a remarkable "brightening" of the magnitudes as displayed by the negative slope of the regression lines. The effect is clearly seen in all filters, with the amount of "brightening" increasing towards smaller aperture size. This is certainly an instrumental effect rather than a real brightening of the target white dwarf star which is a well-known photometric standard. The apparent brightening is due in part to a systematic change in average focus position over the last two and a half years. As indicated above, during the last two focus adjustments the focus was moved into the range of positive positions farther than before. As a result, the average PC focus was close to the optimal value, $d = 0$, unlike the preceding period when the focus spent most of the time in the range of negative values. In other words, the defocusing in the time after the First Servicing Mission through August 1995 was on average larger than afterwards. Hence the sharper PSF that we had since the focus move in August of 1995 made the star in small apertures look brighter.

Table 2. Change in the 10-pixel aperture magnitude of the standard star during the period from April 1994 to October 1996 (Planetary Camera data).

filter	**a_{10} (mag day^{-1} x 10^{-5})^{a}**	**$m_2 - m_1$ (mag)^{b}**
F439W	–6.62 ± 1.59	–0.061 ± 0.014
F555W	–2.77 ± 0.93	–0.026 ± 0.008
F814W	–5.03 ± 1.04	–0.048 ± 0.010

a. a_{10} is the coefficient in equation (1) defining photometric drift corrections for the Planetary Camera.
b. m_1 and m_2 are the magnitudes at the beginning and the end of the period April 1994 through October 1996 as determined by linear regression in Figures 2–4.

There is one more component in the long term magnitude variation, which can be seen in Table 2 for PC data. The Table shows the accumulated change in the magnitude in the 10 pix aperture, close to the reference radius of $\sim 5''$ used by Holtzman et al., 1995b, as defined by the regression lines in Figures 2–4. Magnitudes in the PC have become substantially brighter, by up to 0.06 mag in F439W, since April 1994. Unfortunately, WF3 data cannot be used for comparison because of the recently discovered bug in CALWP2 that made the absolute fluxes measured in WF3 after December 1994 fainter by several percent. The measurements will be repeated in WF3 when the re-calibration of the data is complete, however preliminary indications are that a similar brightening occurred in WF3 as well. Since relative measurements, such as differential aperture magnitudes, will not be systematically affected, the current WF3 results can be used to study the effect of focus on aperture correction.

Whatever the cause of the “brightening” effect, it appears that the photometric zero point (ZP) has drifted away from its original value. Correction for this “photometric” drift which reduces a current ZP to the original ZP can be done by subtracting the amount of magnitude variation defined by the slope of the regression line for the 10 pixel aperture magnitude from the magnitudes measured in a given aperture.

As will be seen in Figures 5–10 below, the magnitudes in the 10 pixel aperture essentially do not depend on focus. In other words, the systematic brightening we see in Figures 3–4 for magnitudes in this aperture must almost entirely be due to the drift of the photometric zero point, which justifies the above definition of ZP "brightening" correction. An approximate correction can be performed by the following equation:

$$m(r) = m_{r,obs}(t_{94}) + a_{10}(t_{94} - t_0) \quad (1)$$

where $m_{r,obs}$ is an observed magnitude within the aperture radius, r, t_{94} is the day number starting January 1st, 1994, and a_{10} is the regression slope for the magnitudes in the 10 pixel aperture. The values of for the PC are listed in Table 2. We set the fiducial day to April 24, 1994 (t_0 = 115), which is when the operating temperature of the CCD was lowered to the current value of –88˚C. In any event, the original zeropoints established by Holtzman et al., 1995b are certainly applicable to the timeframe of April 1994. As discussed above, we expect that the real amount of brightening corrections for WF cameras will be about the same as for PC. However we recommend that the observers do not apply any such corrections to their data until the valid results for WF cameras are obtained and the cause of the photometric drift is understood.

Figure 2: F439W magnitudes in different apertures from the standard star photometric monitoring data. The aperture radius (pixels) is indicated at the right hand side of each data set. Thick lines are linear regressions for the magnitudes in each aperture. The vertical lines indicate the dates of focus adjustment. The left and right panels display the data from the PC and WF3 images, respectively.

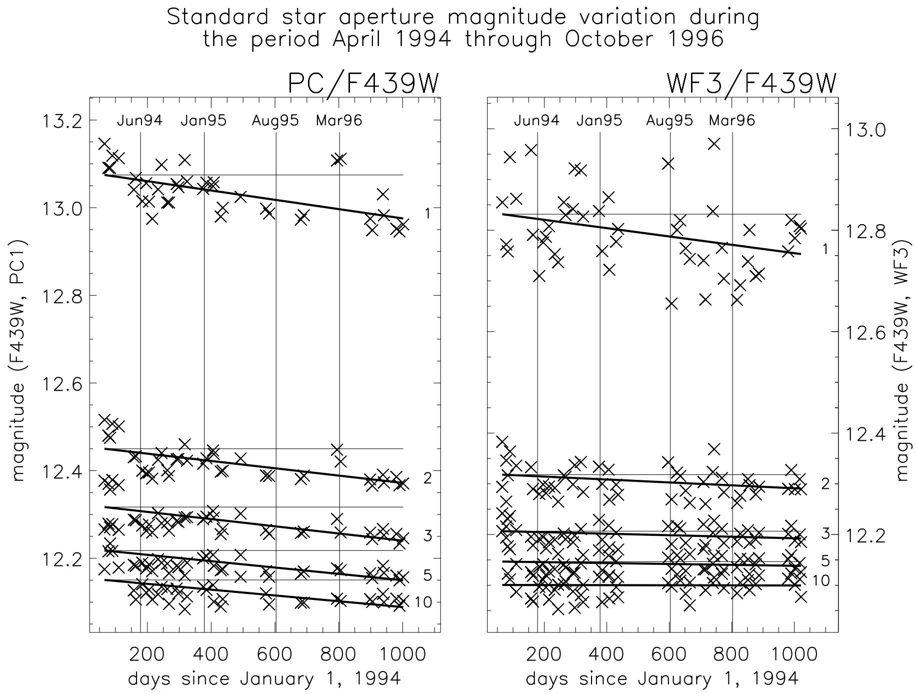


Figure 3: Same as in Figure 2 but for the F555W magnitudes.

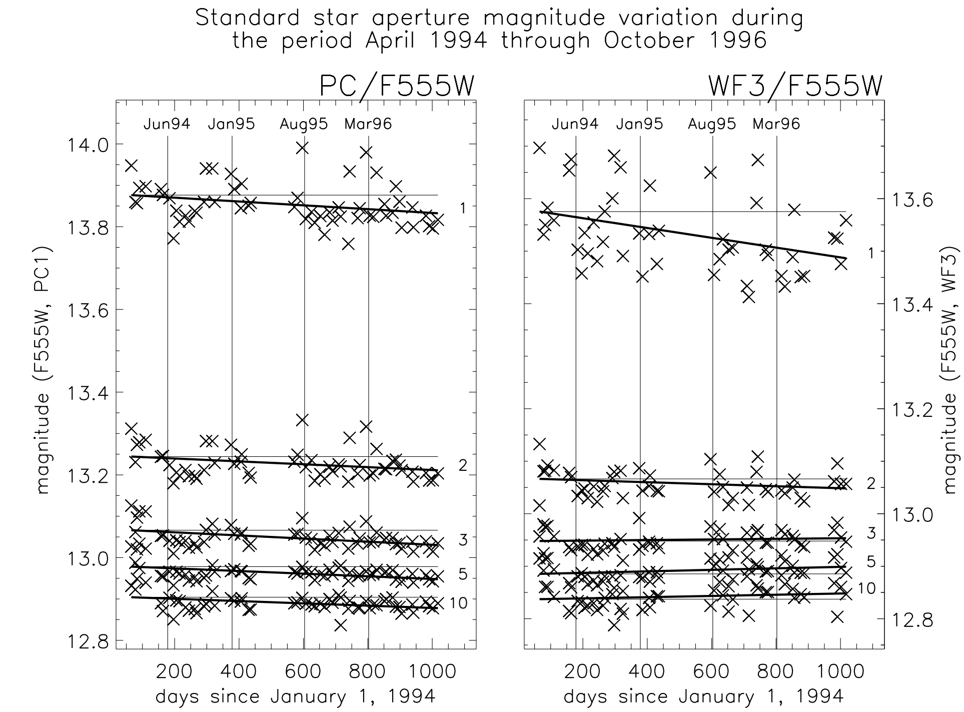
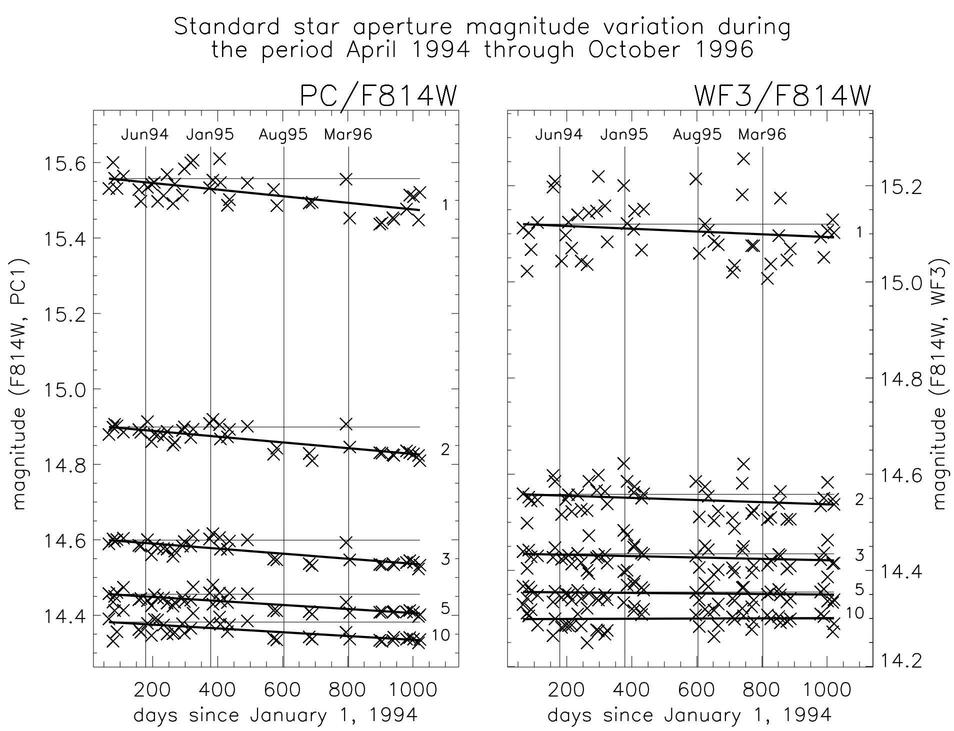


Figure 4: Same as in Figure 2 but for the F814W magnitudes.



4. Correlation between aperture magnitudes and focus position

Since we have the measurements of the focus position at the dates when the photometric monitoring data were taken, we can directly examine the magnitude dependence on focus position for various apertures. The relevant plots are displayed in Figures 5–10. In each case, the left-hand panel excludes the data point from exposures made on May 1st, 1994, when the PC was extremely out of focus at $d \approx -11.5$ µm, and the right-hand panel includes this point. Whether or not this anomalous point is included, the results are consistent with the expected effects of the focus drift on aperture photometry. We did exclude from Figures 5–10 the data points which, for the $r = 1$ pixel magnitudes, were off from the original fitting curve by more than 3 sigma; this resulted in no qualitative changes in the fit but improved by a factor of 2 the accuracy of the fitting curve coefficients.

Figures 5–10 show unambiguously that there is an appreciable impact of the focus drift on the magnitudes derived from small apertures. Within statistical uncertainties, the effect at large is readily explained as being due to defocusing. As the focus drifts away from its optimal value for that detector, the aperture magnitudes become fainter because of the spreading out of the PSF's core, with the amount of magnitude variation going up with decreasing aperture. The magnitude dependence on focus is expected to be nearly quadratic, as is clearly seen from Figure 11 which shows the focus dependence of magnitudes obtained from PSF modeling with *TinyTim*.[1] The data set for PC/F555W displayed in Figure 7 suggests that a second order polynomial is indeed a good fit to the data. The fit for other data sets looks less spectacular and is more uncertain. This is hardly surprising, because focus values for all but PC/F555W data are somewhat compromised by the breathing effect[2]. Also, the quality of other data sets is not as good as that of PC/F555W. In particular, the quality of the F439W images is compromised by larger undersampling in shorter wavelengths and larger contamination by cosmic rays because of longer exposure times used with this filter.

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1. *TinyTim* is a software tool created by John Krist to model WFPC2 PSFs.
2. The focus positions used here were measured from the PC/F555W exposure, and thus, strictly speaking, are valid only for that exposure. By the time the exposures with other camera/filter combinations executed, breathing could have introduced some additional focus variations.

Figure 5: Change of the F439W (PC) magnitude in different apertures due to defocusing. Focus position is from the phase retrieval method applied to the F555W (PC) data. The right panel includes the measurement made for the extreme focus position of $d \approx$ -11.5 μm which occurred on May 1, 1994.

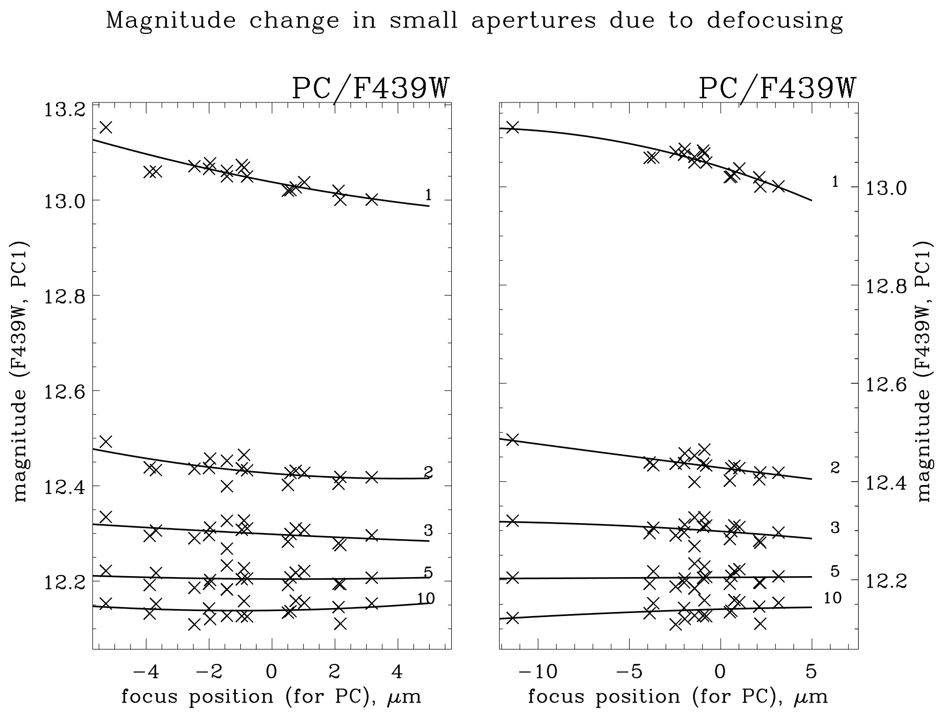


Figure 6: Same as in Figure 5 but for the F439W (WF3) magnitudes. Focus positions are from the F555W (PC) data.

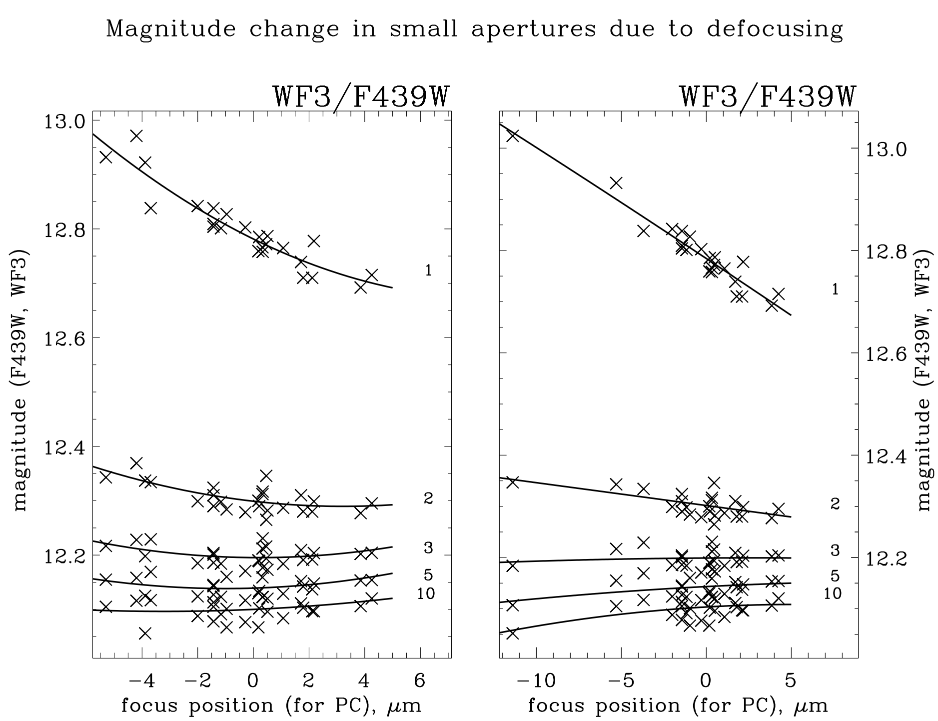


Figure 7: Same as in Figure 5 but for the F555W (PC) magnitudes. Focus positions are from the F555W (PC) data.

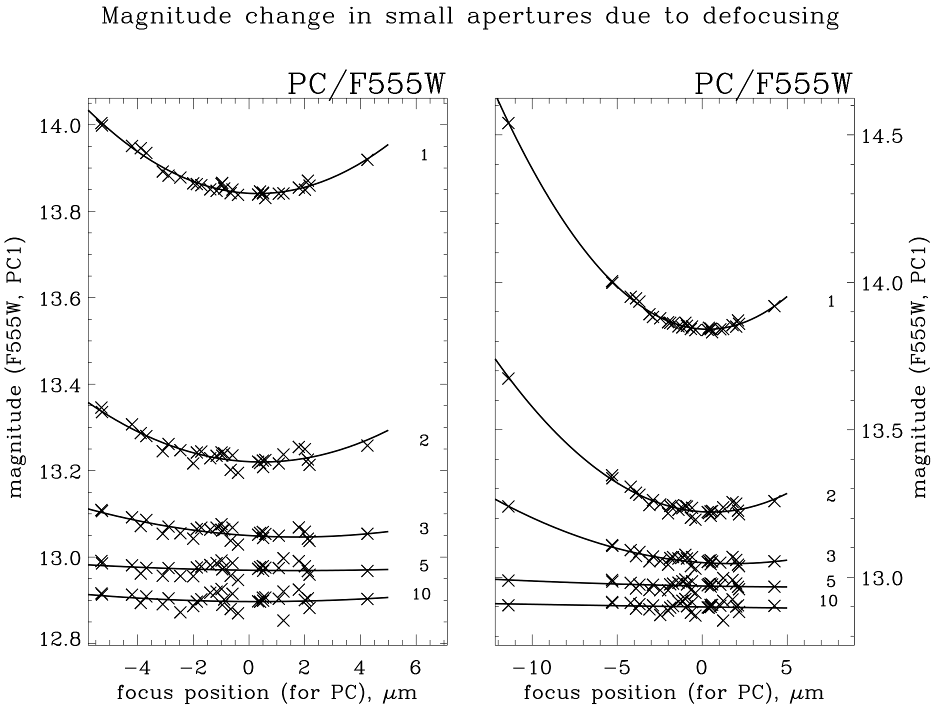


Figure 8: Same as in Figure 5 but for the F555W (WF3) magnitudes. Focus positions are from the F555W (PC) data.

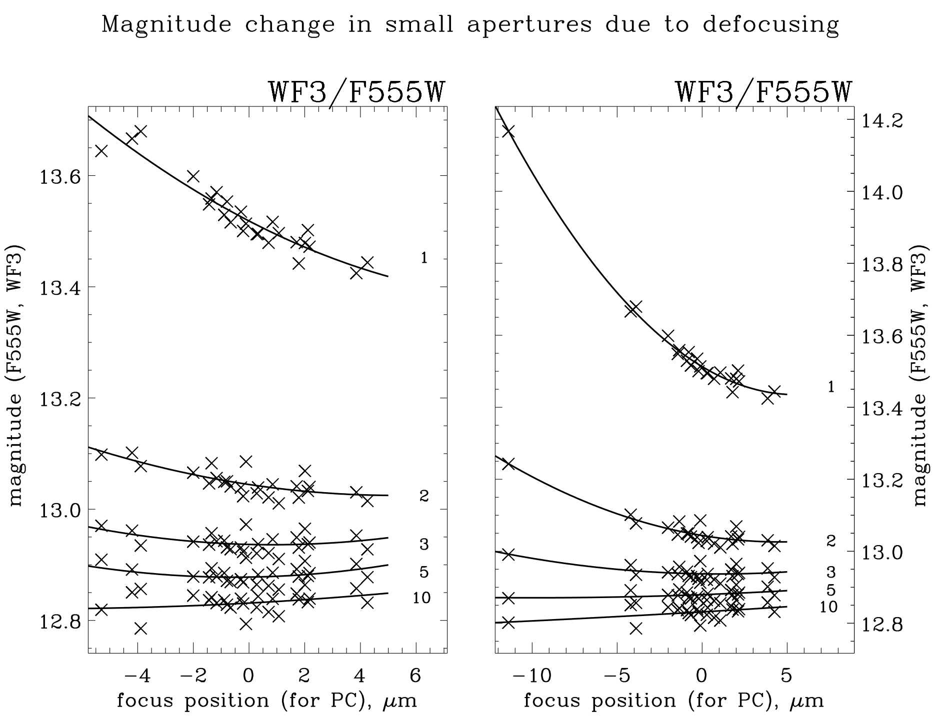
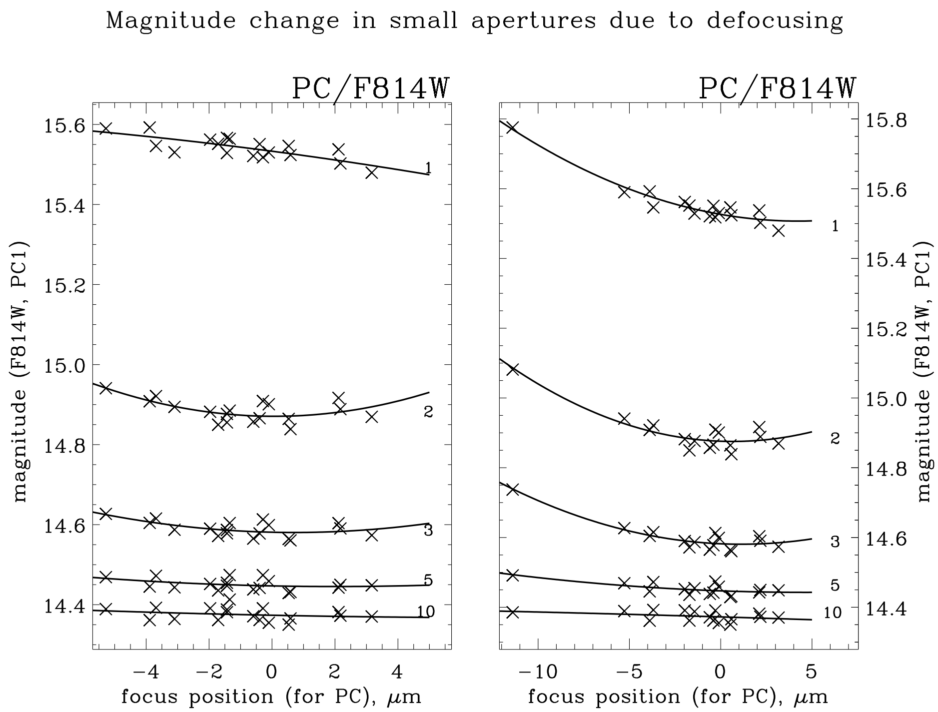


Figure 9: Same as in Figure 5 but for the F814W (PC) magnitudes. Focus positions are from the F555W (PC) data.



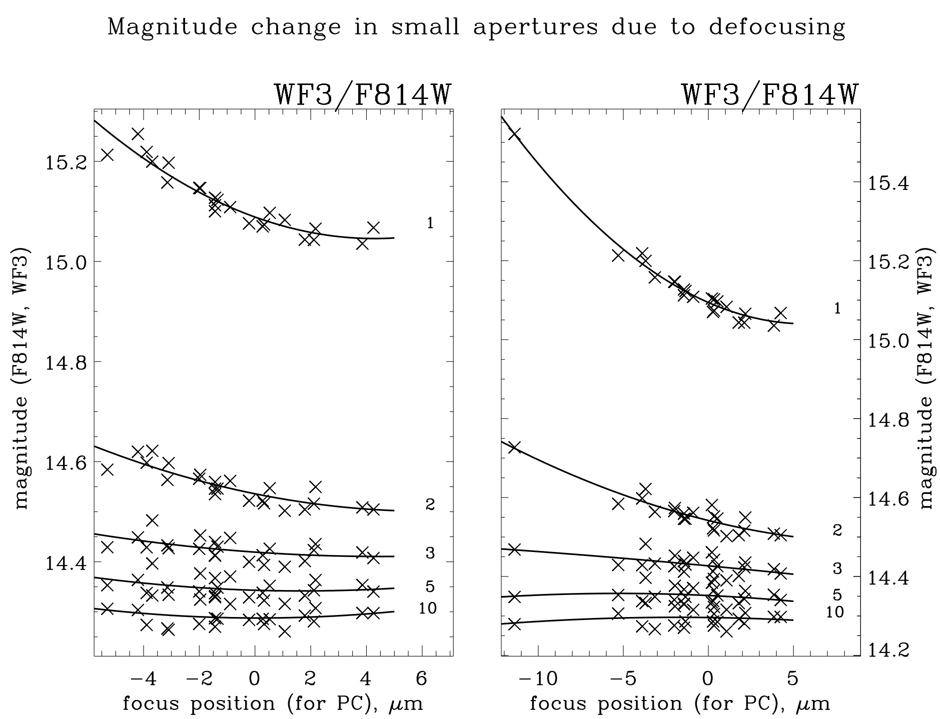
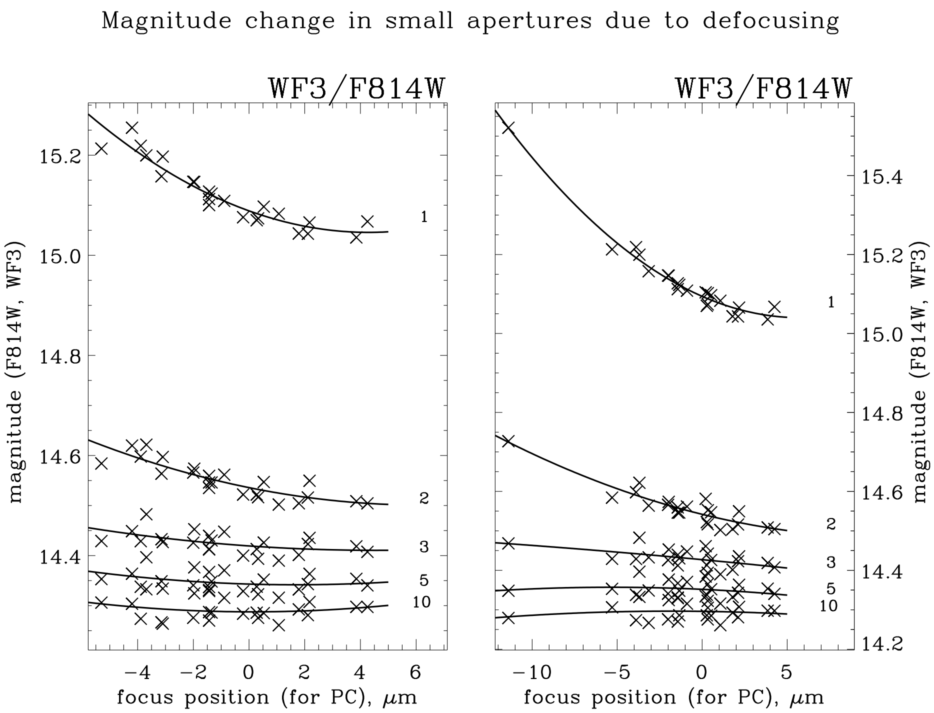


Figure 10: Same as in Figure 5 but for the F814W (WF3) magnitudes. Focus positions are from the F555W (PC) data.



5. Focus offset between the PC and WF3 cameras

Comparison of Figures 7–10 shows that the fitting curves for the PC data are different from those for the WF3 data, suggesting that the WF3 camera focus is offset from that of the PC. (F439W data are omitted in this discussion because of their poor quality mentioned above). The difference is seen especially well in Figure 12 where only 1 pixel aperture magnitudes are displayed. The difference in focus between the cameras was already well-known. Early analysis suggested that the optimal focus for WF3 as obtained from PSF sharpness measurements is offset from the PC optimal focus by 8 to 10 μm (Krist & Burrows 1995). The offset demonstrated by Figure 12 substantiates that result, although the discrepancy we find between the PC and WF3 focuses is somewhat smaller, ~5 μm. Given the uncertainties in both the early estimates and the one following from the positions of a "best photometric" focus in Figure 12, we conclude that our result is consistent with that obtained in the early studies indicated above. It is to be noted that, as seen from Figure 11, the "optimal" focus position derived for WF3 on the basis of the phase retrieval method differs from the "best photometric" focus, where the encircled energy reaches its maximum, by 2 μm in F439W and 1 μm in F814W; this is a natural consequence of their different definitions. If this effect is taken into account, the consistency between the current results and the early measurements of the focus offset is even better.

Figure 11: Focus dependence of magnitudes in the 1 pixel aperture obtained from PSF modeling with TinyTim. The F439W, F555W, and F814W magnitudes are given relative to the magnitude values at the focus position *d* = 0. The focus, *d*, is the own focus of PC and WF3 as opposed to Figures 5–10 where the PC and WF3 data are plotted on the PC focus scale. The curves represent the quadratic fit to the measured magnitudes.

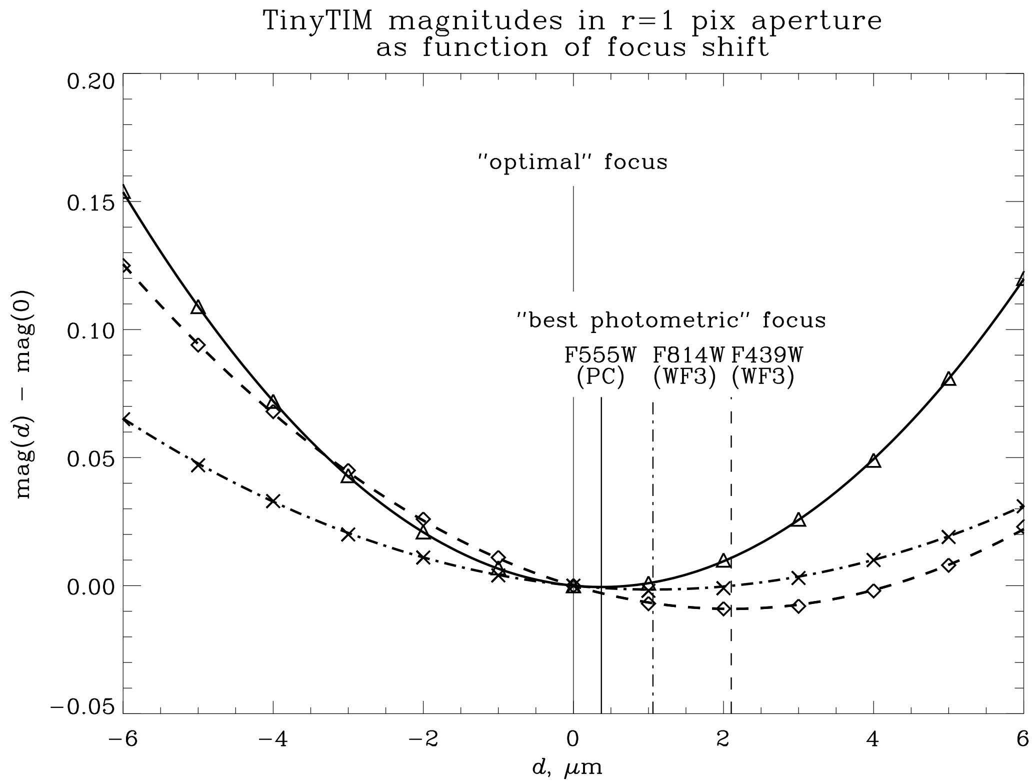


Figure 12: Fitting curves from Figures 5–10 for magnitudes in the 1 pixel aperture. The magnitudes are given relative to the magnitude value at the “optimal” focus position, d. The position of the minimum of each curve (“best photometric” focus) is indicated using the same line style as for the fitting curves. The error bar for the minimum position is indicated as well.

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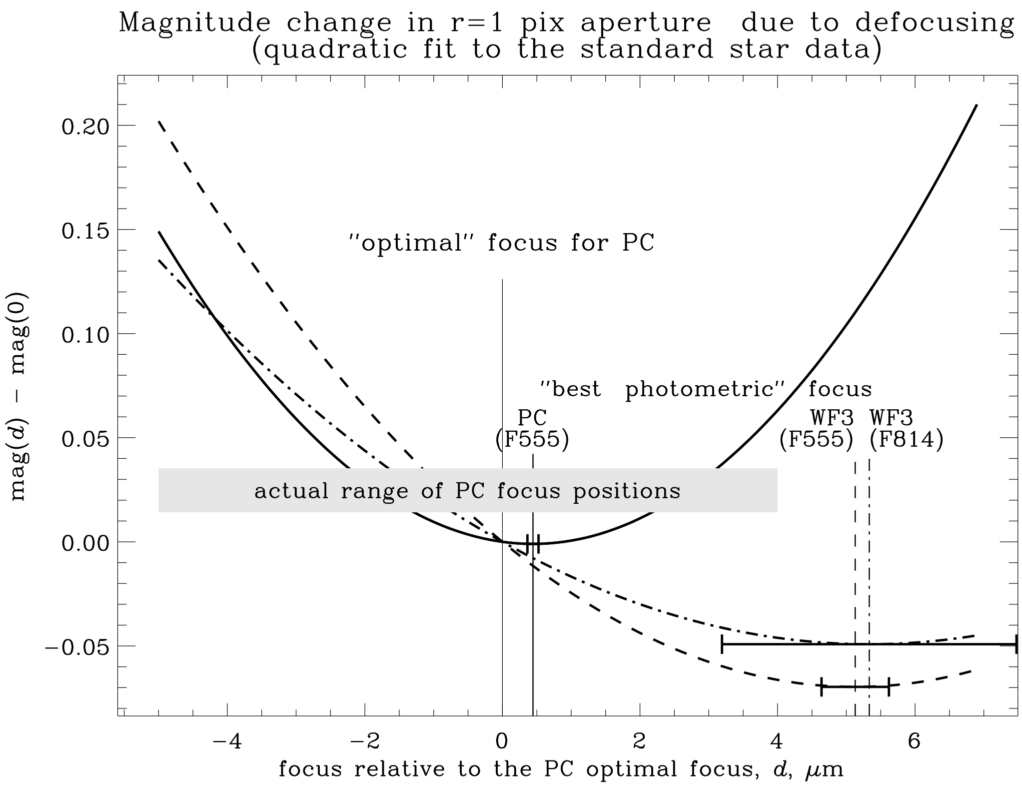

6. Phased aperture corrections

Inspection of Figures 5–10 shows that magnitude corrections for finite aperture size (aperture corrections) should take into account the focus position at the time of observation if small apertures are used for accurate absolute photometry. In other words, aperture corrections for small apertures should be phased with the focus change. Since the dependence of aperture magnitudes on focus becomes negligible for apertures of 10 pixel or larger, we normalize magnitudes to this aperture,

$$m_{r,10} = m_{10} - m_r \quad (2)$$

Phased aperture corrections are then defined as a quadratic fit to $m_{r,10}(d)$ (Figures 13–15):

$$\Delta_{10} m_r(d) = \Delta_{10} m_r(0) + Ad + Bd^2 \quad (3)$$

where m_r are the magnitudes corrected for photometric drift as discussed in Section 3. The coefficients of the fit are given in Table 3. The positive values of B for WF3/F439W are, of course, unphysical but the errors are large, exceeding the estimates of *B*. Thus *B* is just indeterminate in this case.

Strictly speaking, the coefficients in Table 3 are valid only for the centers of the PC and WF3 cameras because the standard star in the photometric monitoring program was always placed in the center of the CCD detector. In general, the issue of the variation of phased aperture corrections across the CCD in each of the WFPC2 cameras has not been investigated, although it could be expected that field variations be smaller than the corrections themselves.

Focus position at any particular date of observation can be estimated from equation

$$d = d_i - 0.025(t_{94} - t_i) \qquad (4)$$

where d_i is the focus position right after focus adjustment, t_{94} is the day number starting January 1, 1994, and t_i is the day when the previous adjustment was done (also starting January 1, 1994). With the coefficients d_i and t_i given in Table 1, this equation yields the piecewise-solid line plotted in Figure 1. Substituting *d* from equation (3) in equation (4), we obtain approximate phased aperture corrections for any desired day of observation from April, 1994, through October, 1996.

Table 3. Coefficients to calculate phased aperture corrections from equation 3.

r (pixel)	$\Delta_{10}m_{r,H}$[a] (mag)	$\Delta_{10}m_r(0)$ (mag)	A (mag μm^{-1}x10^{-2})	B (mag μm^{-1}x10^{-2})
		F439W (PC)		
1	-0.91	- 0.90 +/- 0.04	1.35 +/- 0.42	0.04 +/- 0.05
2	-0.30	-0.29 +/- 0.02	0.83 +/- 0.25	0.01 +/- 0.03
3	-0.16	- 0.16 +/- 0.02	0.48 +/- 0.18	0.01 +/- 0.02
5	-0.07	- 0.06 +/- 0.01	0.09 +/- 0.13	-0.01 +/- 0.01
		F439W (WF3)		
1	-0.73	-0.68 +/- 0.06	2.47 +/- 0.50	-0.03 +/- 0.07
2	-0.23	-0.20 +/- 0.02	0.76 +/- 0.18	- 0.01 +/- 0.02
3	-0.11	-0.10 +/- 0.01	0.27 +/- 0.10	- 0.01 +/- 0.01
5	-0.04	-0.04 +/- 0.01	0.10 +/- 0.08	- 0.01 +/- 0.01
		F555W (PC)		
1	-1.02	-0.94 +/- 0.02	0.31 +/- 0.18	- 0.51 +/- 0.03
2	-0.38	-0.32 +/- 0.01	0.27 +/- 0.11	- 0.32 +/- 0.02
3	-0.19	-0.15 +/- 0.01	0.27 +/- 0.07	- 0.12 +/- 0.01
5	-0.07	-0.07 +/- 0.01	- 0.03 +/- 0.05	- 0.01 +/- 0.01
		F555W (WF3)		
1	-0.77	-0.67 +/- 0.06	2.65 +/- 0.46	- 0.29 +/- 0.06
2	-0.24	-0.21 +/- 0.02	0.86 +/- 0.18	- 0.10 +/- 0.02
3	-0.11	-0.10 +/- 0.02	0.29 +/- 0.13	- 0.04 +/- 0.02
5	-0.06	-0.05 +/- 0.01	0.11 +/- 0.12	- 0.01 +/- 0.02
		F814W (PC)		
1	-1.17	-1.15 +/- 0.04	0.62 +/- 0.39	- 0.12 +/- 0.05
2	-0.52	-0.50 +/- 0.02	- 0.03 +/- 0.22	- 0.16 +/- 0.03
3	-0.22	-0.21 +/- 0.02	0.02 +/- 0.17	- 0.11 +/- 0.02
5	-0.08	-0.07 +/- 0.01	0.04 +/- 0.12	- 0.02 +/- 0.01
		F814W (WF3)		
1	-0.84	-0.79 +/- 0.04	1.94 +/- 0.32	- 0.19 +/- 0.04
2	-0.28	-0.24 +/- 0.02	1.03 +/- 0.19	- 0.07 +/- 0.02
3	-0.14	-0.13 +/- 0.01	0.33 +/- 0.12	- 0.02 +/- 0.02
5	-0.06	-0.05 +/- 0.01	0.13 +/- 0.08	- 0.00 +/- 0.01

a. $\Delta_{10}m_{r,H}$ are aperture corrections based on Holtzman's et al. 1995 Table 2, normalized to aperture radius r = 10 pixel. They are to be compared to "nominal" aperture corrections, $\Delta_{10}m_r(0)$, defined by equation (3).

The aperture corrections at $d = 0$, $\Delta_{10}m(0)$, can be regarded as "nominal" corrections. They can be compared to aperture corrections obtained by Holtzman et al (1995a) from observations of the Omega Cen field soon after the First Servicing Mission. These corrections, $\Delta_{10}m_{r,\,H}$, are given in Table 3 alongside with the coefficients of equation (3). The comparison reveals a good agreement between the "nominal" and Holtzman's corrections. The slightly larger corrections for the smallest apertures in Holtzman et al (1995a) are easily understood assuming that the observations used in that paper were done at a focus position $d \approx -2$ μm rather than at the optimal position, $d = 0$. Given a high degree of consistency between $\Delta_{10}m(0)$ and $\Delta_{10}m_{r,\,H}$, one can use Table 2(a-b) in Holtzman et al (1995a) to translate the normalized corrections from equation (3) to the ones corresponding to an "infinite" aperture radius. The largest radii in Holtzman et al (1995a), $r = 130$ pixel for the PC and $r = 60$ pixel for the WF cameras, are good representation of an "infinite" radius. if one wishes to have such corrections.

Figure 13: Phased aperture corrections for F439W magnitudes normalized to aperture radius $r = 10$ pixel. The solid curves represent the best quadratic fits to the data points; their coefficients are given in Table 3.

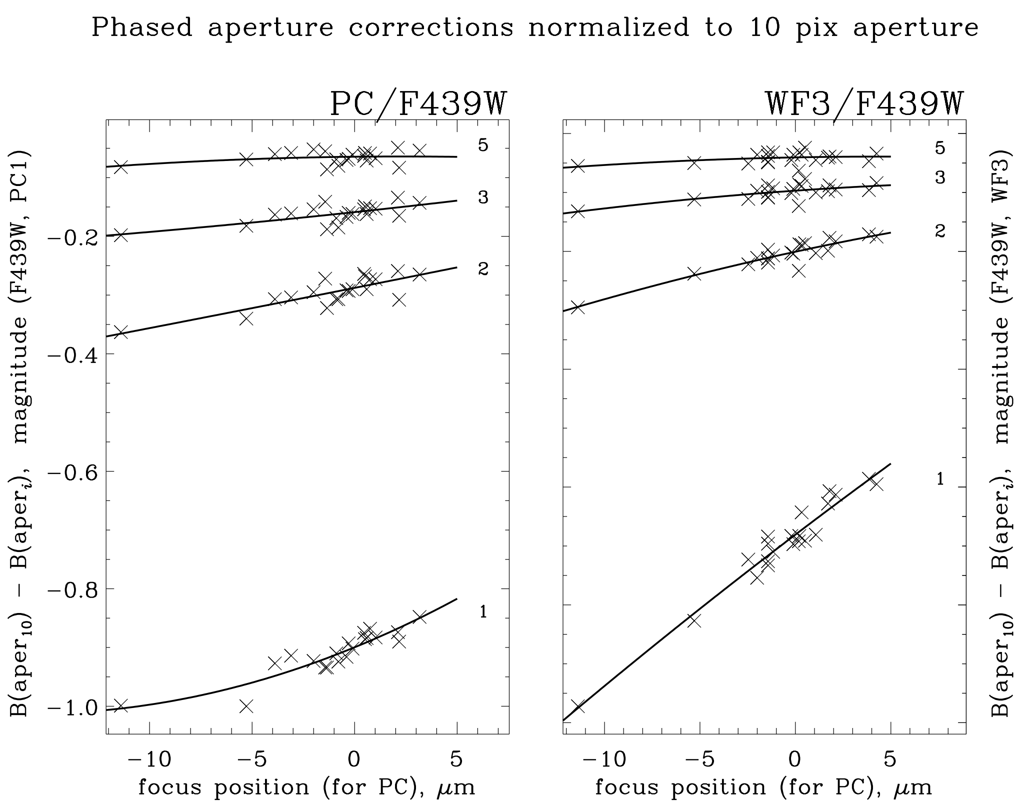

Figure 14: Same as in Figure 13 but for F555W magnitudes.

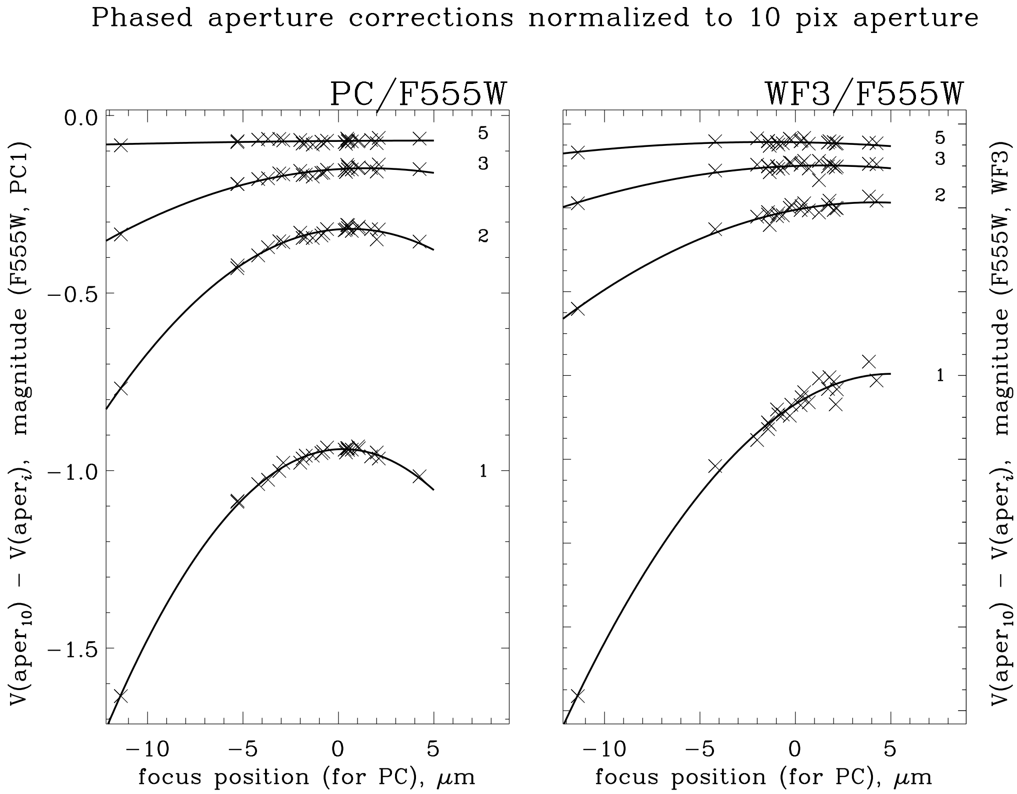

Figure 15: Same as in Figure 13 but for F814W magnitudes.

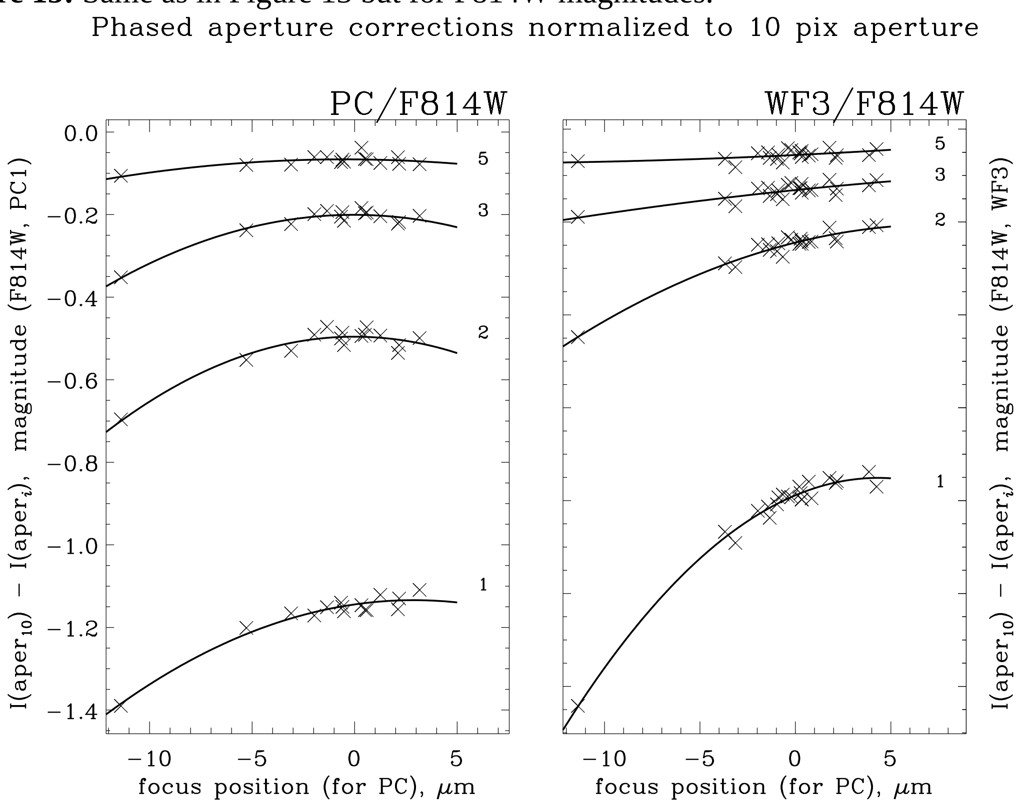

Table 4. Predicted range of flux variations at focus excursions of $\delta d = \pm 2\ \mu m$ around different average focus positions.

r	**range of flux variation (%)**				
(pixel)	$\bar{d}$**[a] = +1**	$\bar{d}$ **= 0**	$\bar{d}$ **= –1**	$\bar{d}$ **= –2**	$\bar{d}$ **= –3**
			F439W (PC)		
1	5.3	5.0	4.7	4.3	6.4
2	3.2	3.0	2.9	2.8	4.2
3	1.9	1.8	1.7	1.6	2.4
5	0.3	0.3	0.4	0.4	0.6
			F439W (WF3)		
1	9.1	9.1	9.1	9.1	13.6
2	2.7	2.8	2.9	3.0	4.5
3	0.9	1.0	1.0	1.1	1.7
5	0.3	0.4	0.4	0.4	0.7
			F555W (PC)		
1	4.0	3.7	5.1	8.3	13.1
2	2.5	2.4	3.4	5.6	8.9
3	0.6	1.0	1.8	2.7	4.2
5	0.2	0.1	0.0	0.1	0.1
			F555W (WF3)		
1	7.7	9.7	11.5	13.1	20.0
2	2.4	3.2	3.9	4.6	7.0
3	0.8	1.1	1.4	1.7	2.6
5	0.3	0.4	0.5	0.5	0.8
			F814W (PC)		
1	1.4	2.3	3.1	4.0	6.2
2	1.5	1.1	1.4	2.1	3.5
3	1.0	0.8	1.1	1.7	2.7
5	0.2	0.2	0.3	0.5	0.8
			F814W (WF3)		
1	5.8	7.1	8.3	9.5	14.4
2	3.3	3.8	4.3	4.7	7.2
3	1.1	1.2	1.4	1.5	2.3
5	0.4	0.5	0.5	0.5	0.8

a. $\bar{d}$ is the average focus position (μm) on the PC focus scale.

7. Effect of "focus breathing"

Table 3 can be used to estimate uncertainties in measured magnitudes caused by focus "breathing". Relative flux variation due to focus excursions of +/-δd from the average focus position $\bar{d}$ can be written as

$$\varepsilon_r(\bar{d}, \delta d) = \frac{(\bar{d} \pm \delta d) - f_r(\bar{d})}{f_r(\bar{d})} = 10^{-0.4[A(\bar{d} \pm \delta d) + B(\bar{d} \pm \delta d)^2]} - 1 \qquad (5)$$

The above equation (and Figure 5) gives an idea on the amount of photometric error that can be introduced by focus "breathing" during the orbital period. As seen from equation (5), the magnitude of the error strongly depends on the average focus position. Table 4 presents flux variations calculated from equation (5) with coefficients from Table 3 for a range of average focus positions and a typical breathing amplitude of +/– 2 µm. The numbers in Table 4 imply that focus breathing appears to be an important factor limiting accuracy that one can achieve with small aperture photometry. Therefore, until better understanding of focus breathing is reached and ways to correct for its effects are found, the observers are recommended either to use apertures of 5 pixel or larger, or to determine aperture corrections from the brightest star in each observation if high absolute photometric accuracy is desired. Breathing may be less of an issue for relative photometry of stars in the same frame, although this area has not been investigated here.

8. Acknowledgments

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