1997 HST Calibration Workshop
Space Telescope Science Institute, 1997
S. Casertano, et al., eds.

Aperture Corrections for WFPC2 Stellar Photometry

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Abstract. We examine the impact of the long term and short term focus position variations on small aperture photometry of WFPC2 images and present aperture corrections phased with the HST focus drift, as well as mean aperture corrections to large aperture radii ("infinity").

1. Introduction

Photometry of point sources in WFPC2 data is usually accomplished using one of 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 (see for example Remy et al. 1997). 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 properly weighted PSF fitting is optimal with respect to maximum S/N extraction.

Aperture photometry is a much simpler procedure which is commonly employed by many astronomers. It is much less sensitive than 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; for example, the published zero points of Holtzman (1995b) refer to an aperture radius r of $0.''5$ (see also Casertano 1997 for more details).

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

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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 error 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 become more important as the aperture radius decreases. For WFPC2, perhaps the most important are focus drift and focus "breathing". So, before we can comfortably use small aperture photometry, we need to examine these factors and find ways to correct for their impact.

The HST focus position, d, has changed systematically at a rate slightly less than 1 μm/month since 1994. The change is believed to be due to the OTA shrinkage induced by desorption of water in the metering truss (Hasan et al. 1993, Casertano 1995), and appears to have slowed significantly in the last year or so (Biretta et al. 1997). 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 HST orbit (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, as well as aperture corrections to large radii ("infinity") averaged over focus variations.

Table 1. History of focus adjustments

date (days)	t_i[a]	adjustment (μm)	d_i[b] (μm)
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 second mirror move, assuming position of +1.5 μm on 6/29/94 and focus drift rate of –0.025 μm per day

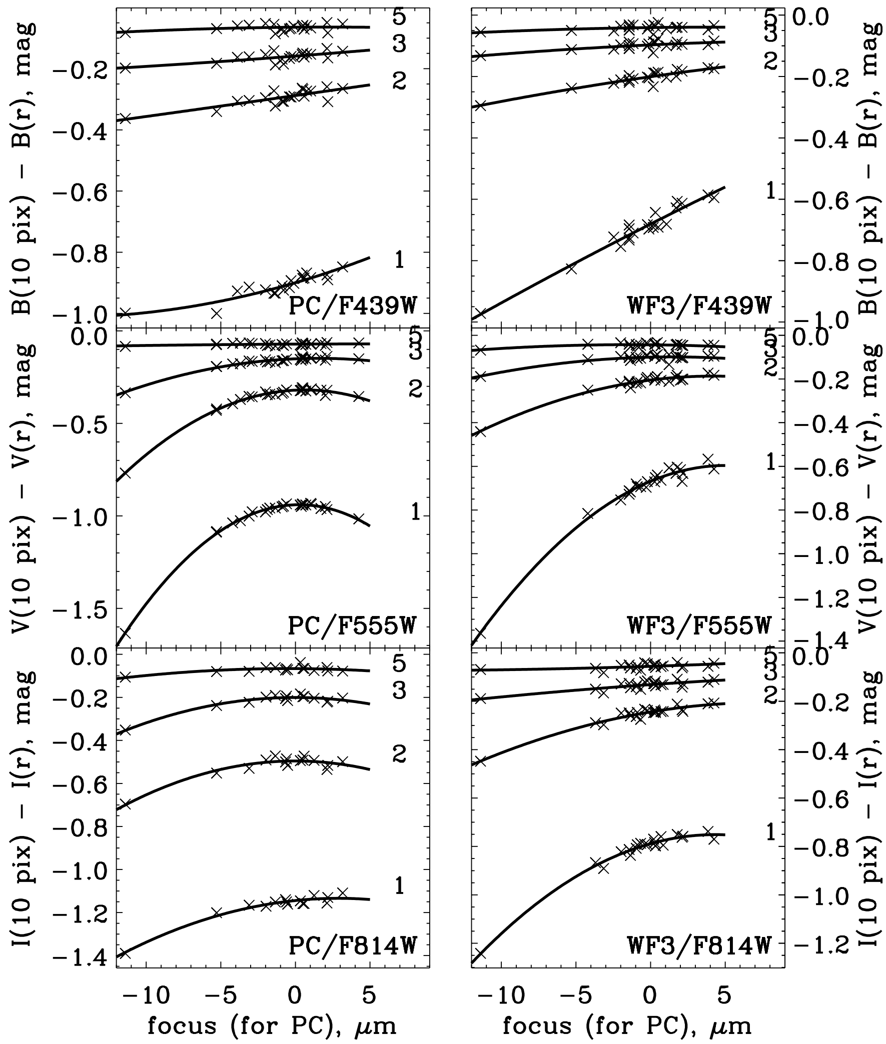

Figure 1. Phased aperture corrections for F439W, F555W, and F814W magnitudes normalized to aperture radius $r = 10$ pixel. The solid curves represent the best quadratic fit to the data points; the fit coefficients are given in Table 2

2. Phased Aperture Corrections

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 study how the measured stellar magnitudes in F555W, F439W, and F814W from the standard star images on PC and WF3 correlate with the focus drift.

To derive the magnitudes of the standard star, we used the `phot` task from the `noao.daophot` package. The magnitudes were measured in aperture radii of 1, 2, 3, 5, and 10 pixels. Sky subtraction was performed using the annulus of 15 pixels, with the parameter `dannulus` set to 5 pixels. Aperture corrections computed from these data for the above aperture radii are plotted against focus position in Figure 1.

Inspection of Figure 1 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,

$$m_{r,10} = m_r - m_{10}. \tag{1}$$

Table 2. Coefficients to calculate phased aperture corrections from equation (2)

r (pixel)	$\Delta_{10} m_{r,H}$ [a] (mag)	$\Delta_{10} m_r(0)$ (mag)	A (mag μm$^{-1} \times 10^{-2}$)	B (mag μm$^{-2} \times 10^{-2}$)
		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 Table 2 of Holtzman et al. (1995a), normalized to aperture radius $r = 10$ pixel. They are to be compared to "nominal" aperture corrections, $\Delta_{10} m_r(0)$, defined by equation (2)

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

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

The coefficients of the fit are given in Table 2. The negative values of B for WF3/F439W are 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 2 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, phased aperture corrections may vary across the CCD in each of the WFPC2 cameras to the extent to which the focus itself varies across the chips.

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

$$d = d_i - 0.025(t_{94} - t_i), \tag{3}$$

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). The coefficients d_i and t_i given in Table 1. Substituting d from equation (3) in equations (2), we obtain phased aperture corrections for any particular day of observation from April, 1994, through October, 1996. The aperture corrections at $d = 0$, $\Delta_{10}m_r(0)$,

Table 3. Predicted range of flux variations at focus excursions of $\delta d = \pm 2$ μm 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

can be regarded as "nominal" corrections. They can be compared to aperture corrections obtained by Holtzman et al. (1995a) from observations of a field in ω Cen soon after the First Servicing Mission. These corrections, $\Delta_{10}m_{r,H}$, are given in Table 2 alongside with the coefficients of equation (2). The comparison reveals a good agreement between the "nominal" and Holtzman's corrections. The correction in Holtzman et al. (1995a) is slightly larger than ours for the smallest apertures, a difference easily understood assuming that the observations used in that paper were done at a focus position $d \sim -2$ μm rather than at the optimal position, $d = 0$. Given the high degree of consistency between $\Delta_{10}m_r(0)$ 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 (2) to the ones corresponding to an "infinite" aperture radius,[1] if desired.

3. Effect of "Focus Breathing"

Table 2 can be used to estimate uncertainties in measured magnitudes caused by focus "breathing". Relative flux variation due to focus excursions of $\pm\delta d$ from the average focus position $\bar{d}$ can be written as

$$\epsilon_r(\bar{d},\delta d) = \frac{f_r(\bar{d}\pm\delta d) - f_r(\bar{d})}{f_r(\bar{d})} = 10^{-0.4[A(\bar{d}\pm\delta d)+B(\bar{d}\pm\delta d)^2]} - 1. \quad (4)$$

The above equation gives an idea on the amount of photometric error that can be introduced by focus "breathing" during the orbital period. As seen from equation (4), the magnitude of the error strongly depends on the average focus position. Table 3 presents flux variations calculated from equation (4) with coefficients from Table 2 for a range of average focus positions and a typical breathing amplitude of ± 2 μm. The numbers in Table 3 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, 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 issue has not been investigated here.

Further details on phased aperture corrections can be found in Suchkov and Casertano (1997).

Table 4. Mean aperture corrections (in magnitudes) and their errors for the WFPC2 photometric filter set at the center of WF3

pix	f336w	err	f439w	err	f555w	err	f675w	err	f814w	err
1	-1.071	0.002	-0.984	0.002	-1.203	0.002	-1.024	0.003	-1.115	0.002
2	-0.237	0.002	-0.194	0.002	-0.284	0.002	-0.243	0.003	-0.242	0.002
3	-0.128	0.002	-0.097	0.002	-0.130	0.002	-0.103	0.003	-0.109	0.002
4	-0.080	0.002	-0.059	0.002	-0.083	0.002	-0.060	0.003	-0.055	0.002
5	-0.053	0.002	-0.039	0.002	-0.054	0.002	-0.041	0.003	-0.037	0.002
6	-0.038	0.002	-0.027	0.002	-0.037	0.002	-0.028	0.003	-0.026	0.002
7	-0.029	0.002	-0.019	0.002	-0.026	0.002	-0.019	0.003	-0.017	0.002
8	-0.022	0.002	-0.015	0.002	-0.018	0.002	-0.013	0.003	-0.012	0.002
9	-0.016	0.002	-0.011	0.002	-0.014	0.002	-0.009	0.003	-0.008	0.002
10	-0.012	0.002	-0.009	0.002	-0.011	0.002	-0.006	0.003	-0.005	0.002
11	-0.008	0.002	-0.007	0.002	-0.009	0.002	-0.005	0.003	-0.004	0.002
12	-0.005	0.002	-0.005	0.002	-0.007	0.002	-0.004	0.003	-0.003	0.002
13	-0.003	0.002	-0.004	0.002	-0.006	0.002	-0.003	0.003	-0.002	0.002
14	-0.002	0.002	-0.003	0.002	-0.004	0.002	-0.002	0.003	-0.001	0.002
15	-0.001	0.002	-0.002	0.002	-0.003	0.002	-0.002	0.004	-0.001	0.002
16	-0.001	0.002	-0.001	0.002	-0.003	0.002	-0.001	0.004	-0.001	0.002
17	-0.000	0.002	-0.001	0.002	-0.002	0.002	-0.001	0.004	-0.001	0.002
18	-0.000	0.002	-0.001	0.002	-0.001	0.003	-0.001	0.004	-0.000	0.002
19	-0.000	0.002	-0.000	0.002	-0.001	0.003	-0.001	0.004	-0.000	0.002
20	-0.000	0.002	-0.000	0.003	-0.001	0.003	-0.000	0.004	-0.000	0.002
21	-0.000	0.002	-0.000	0.003	-0.000	0.003	-0.000	0.004	-0.000	0.003
22	-0.000	0.002	-0.000	0.003	-0.000	0.003	-0.000	0.004	-0.000	0.003
23	-0.000	0.003	-0.000	0.003	-0.000	0.003	-0.000	0.004	-0.000	0.003
24	-0.000	0.003	-0.000	0.003	-0.000	0.003	-0.000	0.004	-0.000	0.003
25	-0.000	0.003	-0.000	0.003	-0.000	0.003	-0.000	0.004	-0.000	0.003

[1] The largest radii in Holtzman et al. (1995a) are $r = 130$ pixel for PC and $r = 60$ pixel for WF cameras.

4. Mean aperture corrections to large radii

The data accumulated since 1994 allow a better determination of the aperture correction to large radii than could be obtained in Holtzman et al. (1995). These new corrections were obtained from composite images of the primary standard GRW+70d5824 at the center of WF3. For the composites, we used 41 individual images in f336w, 31 images in f439w, 38 images in f555w, 31 images in f675w, and 37 images in f814w. We performed aperture photometry on each composite image, with the results shown in Table 4 and in Figure 2. The sky background was calculated in the annulus 26 to 30 pixels; the uncertainty in the sky value dominates the uncertainty in the aperture correction, and therefore the errors are highly correlated from one radius to the next. As seen in the Table, the corrections appear to be smaller than 0.001 mag, and actually vanish within the measurement error, at radii of approximately 20 pixels. The data thus suggest that the WFPC2 aperture corrections to large radii should be typically smaller than a few millimagnitudes for aperture radii larger than 20 pixel ($\sim 2''$).

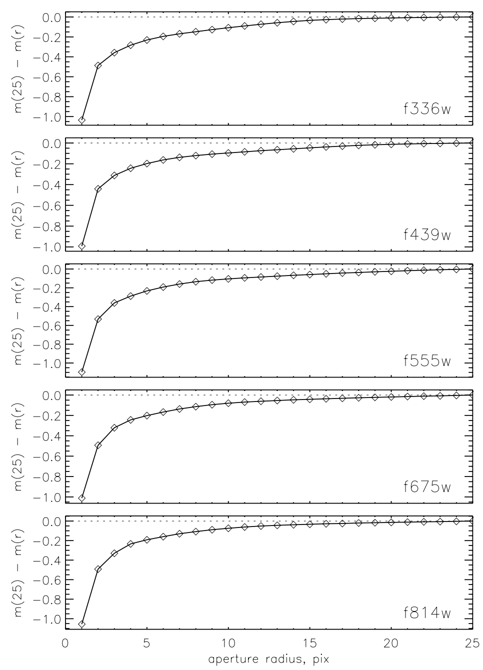

Figure 2. Mean aperture corrections, in magnitudes, for WF3, normalized to aperture radius $r = 25$ pixel.

References

Biretta, J., et al., 1997, Instrument Science Report WFPC2 97-09 (Baltimore: STScI)

Casertano, S., 1995, Instrument Science Report OTA 18

Casertano, S., 1997, this volume

Hasan, H., & Bely, P.Y., 1994, in *The Restoration of HST Images and Spectra II*, eds. R.J. Hanish & R.L. White (Baltimore: STScI), p. 157

Hasan, H., Burrows, C.J., & Schroeder, D.J., 1993, PASP, 105, 1184

Holtzman, J., et al., 1995a, PASP, 107, 156

Holtzman, J., et al., 1995b, PASP, 107, 1065

Remy, M., Surdej, J., Baggett, S., & Wiggs, M., 1997, this volume

Suchkov, A., & Casertano, S., 1997, Instrument Science Report WFPC2 97-01

Whitmore, B., 1995, in *Calibrating Hubble Space Telescope: Post Servicing Mission*, eds. A. Koratkar & C. Leitherer, p. 269