FOC PSF Monitoring Program for Cycles 4-6

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ABSTRACT

This report describes the PSF monitoring calibration for the FOC for cycles 4-6. It also documents the secondary mirror and COSTAR moves made since the First Servicing Mission in late 1993.

1. Introduction

The Faint Object Camera PSF is very sensitive to small focus errors, since it samples the diffraction-limited PSF down to 3200 Å. For this reason, the 6-monthly cycle of adjusting the secondary mirror to keep WFPC2 in focus is insufficient to preserve the FOC image quality. Over Cycles 4-5, the mean OTA desorption rate was approximately 0.7μ/month. This means that the HST focus can vary by approximately +/-2μ over the course of 6 months. When added to the typical visit-level variations of approximately 1μ around the mean focus position, and the inter-orbit "breathing" amplitude variation of typically 2μ, it is easy to see that focus excursions of 5μ or so would not be uncommon for FOC observations if the focus were only corrected every 6 months.

2. The Effect of Focus Errors on the FOC PSF

Because the residual aberrations of the FOC PSF are small, it is very difficult to determine the focus accurately using the usual methods (phase retrieval, sharpness, pseudo-Strehl, encircled energy). At wavelengths where phase retrieval works well (>4000 Å), the performance degradation due to focus errors is not large, and the sign of the focus error is indeterminate. At shorter wavelengths, where the pseudo-Strehl and sharpness are quite strong functions of focus, phase retrieval does not work well so it is difficult to use empirical measurements of FOC PSFs to relate PSF degradation to defocus, since the latter is undetermined. This indicates the need for model FOC PSFs to determine how focus errors affect the FOC PSF.

To determine the effect of focus on the FOC PSF, a series of TinyTim PSFs was calculated, using a set of wavelengths (1200, 2000, 3000, 4000, 5000 Å) and defocus settings (corresponding to 0, 1, 2, 4, 6, 8μ of secondary mirror despace), a total of 30 PSFs in all. The PSFs were monochromatic, use the standard TinyTim FOC+COSTAR aberrations, and were constructed to have an image size of 3x3 arcsec (210x210 pixels). Each PSF has a total integrated flux over the whole image of 1.0.

The most critical performance measure for FOC data is the pseudo-Strehl ratio, or the fraction of the flux in the central pixel. This is plotted below for the TinyTim PSFs, along with some values for actual FOC PSFs taken from various calibration programs. It can be seen that the "good" PSFs taken in 1994 follow the overall trend of simulated PSFs with a focus error of less than 2μ, which shows that the measured pseudo-Strehl ratios of in-focus PSFs follow the same behavior as the TinyTim simulations both in the absolute values and in the existence of a peak in the apparent pseudo-Strehl ratio at near-UV wavelengths.

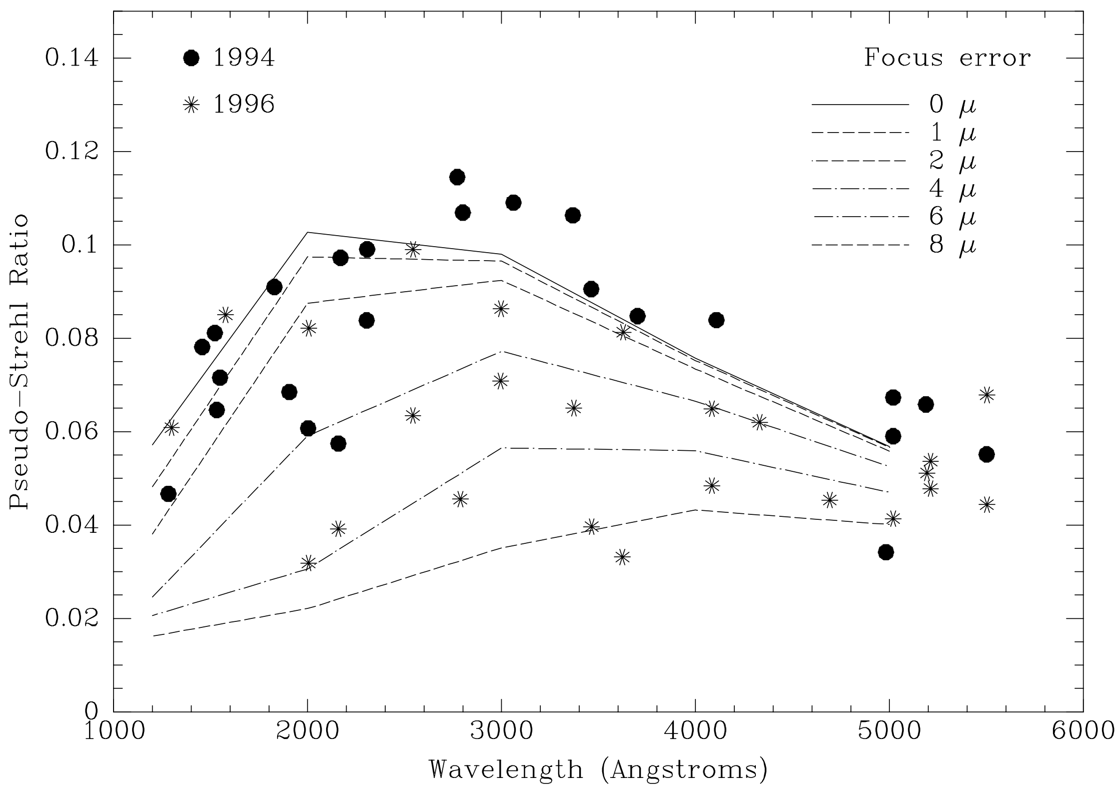

Figure 1: The fraction of light contained in the central pixel is plotted for various TinyTim PSFs and for real FOC PSFs taken when the telescope focus was good (1994) and when the focus was bad (1996).

The situation for out-of-focus PSFs is also equally well-modeled by the TinyTim simulations. Phase retrieval of PSFs taken in 1996, when the focus was bad, indicated focus errors of 6-8μ, and this agrees with the TinyTim simulations. This validation of the TinyTim PSFs indicates that it is not unreasonable to use the behavior of the simulated PSFs to explore the effect of focus errors on the FOC PSF.

It can be seen from Figure 1 that focus effects are largest in the ultraviolet, and quite mild in the visible. Whereas a 4μ defocus can reduce the pseudo-Strehl by half in the 1200 Å region, at 5000 Å the effect is less than 10%. But the point is made that a 5μ focus error can be disastrous for FOC observations of point sources in the ultraviolet.

3. Strategy for Correcting the FOC focus

There is nothing that can be done operationally to correct for either breathing or visit-dependent focus effects, but the effect of long-term desorption can be mitigated by altering the focus at more frequent intervals than the 6-month cycle that is appropriate for WFPC2. Rather than moving the secondary mirror more frequently, it is possible to use the fact that the COSTAR deployable optical bench (DOB) provides +/- 8mm of focus control (equivalent to +/- 40μ of secondary mirror motion), and is rated for many hundreds of cycles of operation. This provides a natural way to control the focus for the FOC (and, incidentally the FOS and GHRS, although their requirements for focus control are even less strict than those of WFPC2) without incurring the (slight) risk of a failure in the secondary mirror actuators.

The frequency at which the COSTAR DOB should be moved is guided by the relative sizes of the desorption rate, breathing amplitude and visit-dependent focus. Over cycles 4 and 5, the desorption rate (as measured by periodic monitoring using WFPC2) was approximately -0.75μ/month. Thus over 6 months, the focus changes by +/- 2.25μ. Adding to this the visit-dependent focus term of r.m.s 1μ and breathing with an amplitude of 2μ gives a complex relation between the focus error and the fraction of time the focus error is at least as bad as the given error. In principle, it would be possible to set a quantitative condition for optimizing the period between DOB moves (e.g. the focus error should be 5μ or more for no more than 10% of the time), but in practice, the procedure was to observe that relying on the 6-monthly WFPC2/secondary mirror correction rate was insufficient, leading to PSFs that were visually and quantitatively degraded, whereas moving the DOB every 3 months eliminated these events.

After the DOB position was initially set to 0.0mm during the FOC/COSTAR SMOV phase, it was expected that it would not be necessary to refocus the telescope very often; the pre-COSTAR aberrated PSF was very insensitive to defocus. FOC images taken through May 1994 still appeared to be in focus. However, a gap of over a month without any images suitable for evaluating the PSF quality was followed by images where the degradation in quality was clear. This was particularly obvious for near-ultraviolet images of a crowded (globular cluster) field. A secondary mirror move was planned for just after these images, moving the secondary by 5μ away from the primary to counteract the ~6 months of desorption, and the subsequent FOC images appeared to be OK. To make sure, some small DOB moves were made and UV PSF images were taken to verify that the performance was close to the optimum.

Following this, is was decided that a more robust way of handling the FOC focus was required. A calibration proposal was written to provide the COSTAR/DOB move opportunities and to monitor the effect of the moves. This proposal (with ID 5762) was continued through Cycle 5 (ID 6162), Cycle 6 (ID 6895) and Cycle 7 (ID 7686). The general form for the proposal was:

- Move the COSTAR DOB by an amount to compensate for approximately 3 months of desorption, taking into account the image quality and focus measurements in the previous three months.
- Take confirmatory images in the near-UV and F486N filters
- Wait 3 months
- Move the DOB back to its former setting, around the time of a secondary mirror move
- Take more confirmatory images.
- Wait 3 more months

This keeps the COSTAR/DOB moves in sync with the secondary mirror moves. Since the COSTAR moves also affect the spectrographs, some coordination is required to ensure that the DOB moves do not straddle critical observations for which a significantly different focus could lead to anomalous or misleading results.

The timetable for secondary mirror moves and DOB moves is given below, in Table 1. For reference, moving the DOB by -1mm will correct the effect of 5.4μ of secondary mirror desorption.

Note that some of the COSTAR move opportunities were not used, in particular the window in late 1995. This arose because phase retrieval appeared to show that the FOC focus was optimally set at that time. However, little was known about how visit-dependent focus effects could bias individual focus measurements, and FOC focus measurements were too small in number to average out such effects. Since the COSTAR DOB was not moved from –0.1mm to ~–0.7mm at the end of 1995, it was not necessary to move it back to –0.1mm in early 1996.

Also, it can be seen that the focus move in early 1997 was in the POSITIVE direction, in the same direction as desorption. This is because the desorption rate had significantly slowed down in the time since it was initially measured in 1994, and the desorption moves in 1995-1996 had overcompensated for desorption. The WFPC2 focus was therefore significantly positive with respect to the optimum, so an inward move of the secondary mirror was required to bring the focus closer to the WFPC2 optimum.

Table 1: Timetable for COSTAR DOB and secondary mirror moves, 1994-1997

Date	Type of move	Amount (μ)	DOB from	DOB to	Comments
1994.010	DOB			0.0mm	Initial Setting
1994.180	SM	–5			
1994.221	DOB		0.0mm	–0.2mm	"Check"
1994.297	DOB		–0.2mm	–0.8mm	
1995.015	SM	–5.5			
1995.015	DOB		–0.8mm	–0.1mm	
1995.135	DOB		–0.1mm	–0.7mm	
1995.240	SM	–6.5			
1995.240	DOB		–0.7mm	–0.1mm	
1995.330	DOB	not moved			
1996.075	SM	–6.0			
1996.075	DOB	not moved			
1996.190	DOB		–0.1mm	–0.65mm	
1996.304	SM	–5.0			
1996.304	DOB		–0.65mm	–0.2mm	
1997.077	SM	+2.5			
1998.033	SM	–2.4			

4. Analysis of the monitoring data

The data taken as part of the PSF monitoring program is slightly different from observing cycle to cycle, but all the programs share the acquisition of at least one image in the 256X256 format using the F486N filter. Each program also has a UV image, although the filter changes from cycle to cycle. In almost all cases, the target is the UV spectrophotometric standard star BPM16274. The F486N images are intended for phase retrieval, the UV images were for pseudo-Strehl analysis.

Phase retrieval of the F486N images

Phase retrieval is a method used to determine the low-order aberrations of an optical system by analysis of the PSF. It involves creating a PSF with a trial set of aberrations, perturbing those aberrations by a small amount and observing the effect on a figure-of-merit, and then using the changes in the figure of merit to derive a new “best” set of aberrations to describe the optical system. It has been used extensively to parametrize the Hubble Space Telescope optical system (see Burrows et al. (1991): “The Imaging Performance of the Hubble Space Telescope”, *Ap. J. Letters*, **369**, L21, and Krist & Burrows (1995): “Phase-retrieval analysis of pre- and post-repair Hubble Space Telescope images”, *Applied Optics*, **34**, 4951).

Phase retrieval is a useful tool in monitoring the focus, since it gives a quantitative measure of the focus error which does not require external calibration. Unfortunately, when the PSF image is very close to its diffraction-limited form and when residual aberrations are very low, the sign of the focus error is indeterminate. Small amounts of astigmatism are particularly good at resolving the focus error sign discrepancy; unfortunately, the COSTAR-corrected FOC PSF has almost no residual astigmatism.

The phase retrieval code used for analysis of the FOC F486N images was borrowed from John Krist, using updates introduced by George Hartig to account for COSTAR and to correctly sample the HST secondary pupil map. The code is written in IDL. The routine “newmaps” is used to ensure that the new primary and secondary mirror maps are used and that the FOC position on the secondary is used. N_{crit} is set at 256. Curvefit with merit function power = 2.0, merit wing damping = 0.005 and 0 flexible parameter is used. The focus, X-coma, Y-coma, X-astigmatism, Y-astigmatism, X-tilt and Y-tilt are fitted for, while the spherical aberration is set to -0.012μ rms, the pixel size is set to 25μ, the X- and Y-jitter are set to 13mas, the mirror map X-field is set to -4.03 arcmin and the Mirror map Y-field is set to -2.35 arcmin (the defaults).

When extracting the PSF to be fitted, the dynamic range is set to “large”, and the extracted PSF size is generally set to 63 pixels. The phase retrieval code is set in motion with the somewhat cryptic invocation: fitb, ‘x2ur0406t’,0,1,1

The results of the phase retrieval analysis are given in Table 2. The conversion factor of 0.01μ of rms wavefront error corresponds to 1.62μ of secondary mirror displacement was used. Since the sign of the focus error is not determined from phase retrieval, the focus error is preceded by a ± sign. The next column, the nominal focus, gives the focus determined from the fit to WFPC2 observations, with the COSTAR DOB position added in to give the net focus value.

Recently, a model has been developed by John Hershey at STScI to try and account for the visit-level focus variations. This model is purely phenomenological, and incorporates the history of various attitude parameters weighted in such a way as to provide a good fit to a large body of WFPC2 focus measurements. The model provides a measure of the deviation of the focus from the nominal value at the time of observation, and is listed in the sixth column of Table 2. The final column is the sum of the previous two, which should give a good estimate of the actual telescope focus at the time of the PSF monitoring observations. The Hershey model values were obtained from the OSG HST Focus WWW page

Table 2: Results of the Phase Retrieval Analysis

Image Name	Date of observation	Focus rms (μ)	Focus error (μ SM)	Nominal focus	Model deviation	Net focus
x2ji0204t	1994.298	0.0417	±6.8	2.4	2.2	4.6
x2ji0404t	1995.018	–0.0073	±1.2	1.1	0.5	1.6
x2ji0604t	1995.155	–0.0143	±2.3	0.9	2.4	3.3
x2ur0206t	1995.243	–0.0174	±2.8	2.1	–2.8	–0.7
x2ur0207t	1995.243	–0.0247	±4.0	2.1	–3.4	–1.3
x2ur0406t	1995.336	–0.0006	±0.1	0.1	–1.4	–1.3
x2ur0407t	1995.336	0.0165	±2.7	0.1	–2.4	–2.3
x2ur0606t	1996.020	–0.0003	±0.0	–0.8	2.0	1.2
x2ur0607t	1996.020	–0.0088	±1.4	–0.8	1.3	0.5
x2ur0806t	1996.076	0.0207	±3.4	4.2	0.6	4.8
x2ur0807t	1996.076	0.0115	±1.9	4.2	–0.3	3.9
x3cr0206t	1996.191	0.0257	±4.2	5.3	0.4	4.9
x3cr0207t	1996.191	0.0125	±2.0	5.3	0.1	5.2
x3cr0406t	1996.338	0.0356	±5.8	5.8	1.0	4.8
x3cr0407t	1996.338	0.0493	±8.0	5.8	1.4	4.4
x3cr0606m	1997.198	0.0261	±4.2	0.8	–4.0	–3.2
x3cr0607m	1997.198	0.0310	±5.0	0.8	–4.0	–3.2
x3cr0806r	1997.298	0.0047	±0.8	–1.2	0.1	-1.1
x3cr0807r	1997.298	–0.0036	±0.6	–1.2	-0.5	-1.7

(**`http://www.stsci.edu/ftp/instrument_news/Observatory/focus/focus2.html`**).

Plotting the measured focus error against the telescope focus should tell us the offset between the WFPC2 and COSTAR+FOC foci. The results of such a plot are in Figure 2, where the measured focus is plotted against the Nominal focus from Table 2. Since the measured focus error has no sign information, each point was plotted twice, with a solid symbol giving the +ve value and an empty symbol the -ve value. If there were a perfect correlation between the measured and predicted focus values, then the points would form an “X” pattern, with the crossover point showing the offset between the COSTAR and WFPC2 foci. In practice, the correlation is pretty good with a few discrepant points at the high focus values. Straight lines of slope 1 and –1 are superimposed over the distribution of points, with the intercept estimated by eye to be at approximately +1μ. This means that the FOC focus should measure zero when the OTA focus is zero and the COSTAR DOB is set to +1μ, or -0.2mm, which is the current setting.

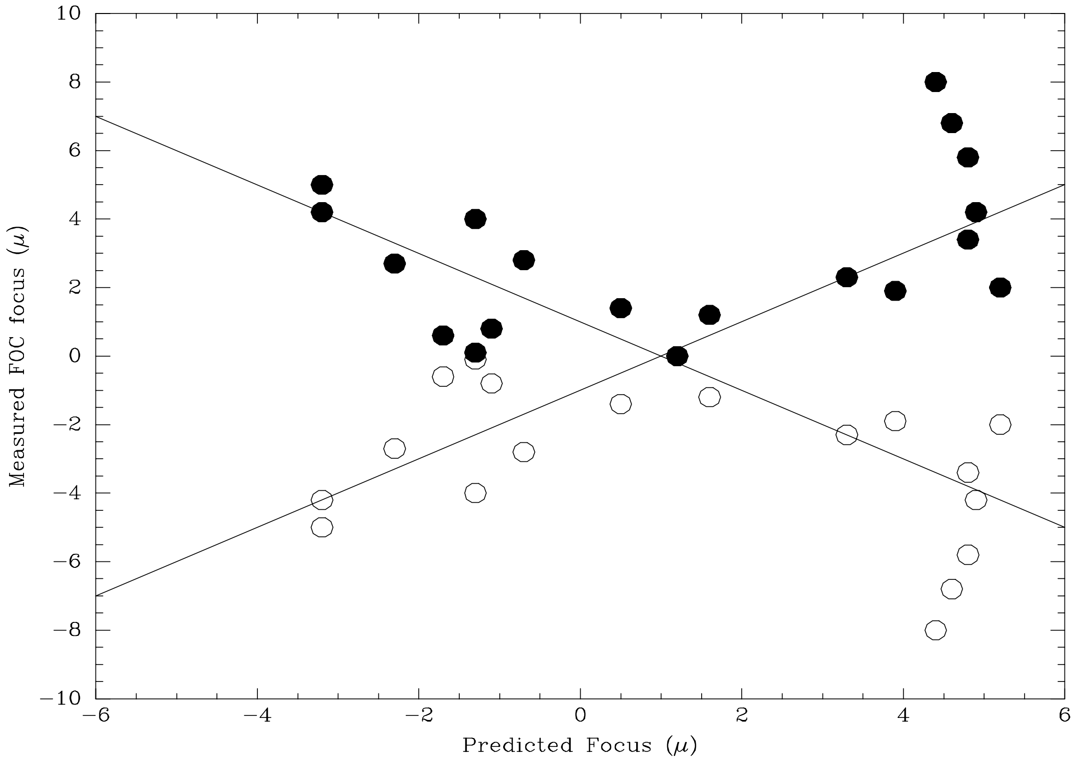

Figure 2: Focus (as measured by phase retrieval analysis) for FOC F486N images plotted against the predicted focus position (as determined by combining the WFPC2-determined nominal focus with the Hershey model for predicting visit-dependent focus). Each point is plotted twice, with the solid symbol representing a +ve focus measurement and the open symbol an exactly equal -ve measurement. If the focus measurements followed the predictions exactly, the points would fall on a cross-shaped pattern with the intercept giving the focus offset between COSTAR+FOC and WFPC2.

Analysis of the UV images

As well as the F486N images, exposures were taken of the same star using the F278M filter. As can be seen from Figure 1, the pseudo-Strehl ratio is a strong function of focus at this wavelength, although there is no sensitivity to the sign of the focus error. However, the dependence of pseudo-Strehl on focus has a parabolic form, in contrast to the linear dependence of phase-retrieved defocus on actual defocus.

The data from the Cycle 4 version of this proposal (#5762) used the F120M and F220W filters to monitor the defocus. Since there are only a small number of F220W exposures, they provide little information. However, the F120M filter was used in several other programs, most notably the UV monitoring program, so the effect of defocus on the pseudo-Strehl in the F120M filter will be considered along with that using the F278M filter.

Since the UV PSF is undersampled, it is necessary to measure the pseudo-Strehl ratio in the raw (i.e., not geometrically corrected) images. The lack of flatfielding does not affect the results appreciably, since the PSF was placed in a virtually identical position for all images. The results of the pseudo-Strehl analysis are presented below, in Tables 3 (F120M) and 4 (F278M), and plotted in Figures 3 and 4.

Table 3: Resuls of pseudo-Strehl analysis of F120M data

Dataset	Date	Pseudo-Strehl (%)	Focus					
			OTA (μ)	COSTAR (mm)	COSTAR (μ)	Net (μ)	Model Delta (μ)	Overall (μ)
x2340102t	1994.023	4.67	3.0	0.0	0.0	3.0	–0.1	2.9
x2ap010bt	1994.083	5.28	0.5	0.0	0.0	0.5	–0.3	0.2
x2fn0102t	1994.165	3.25	–2.5	0.0	0.0	–2.5	0.2	–2.3
x2fn0202t	1994.273	4.37	–1.1	–0.2	1.1	0.0	–0.7	–0.7
x2fn0302t	1995.032	4.95	0.2	–0.1	0.5	0.7	0.7	1.4
x2fn0402t	1995.154	5.22	–2.9	–0.7	3.8	0.9	1.8	2.7
x2fn5102t	1994.216	6.52	0.7	0.0	0.0	0.7	–1.6	–0.9
x2fn6102t	1994.222	6.10	0.5	–0.2	1.1	1.6	–0.2	1.4
x2ji0202t	1994.298	2.81	–1.9	–0.8	4.3	2.4	1.7	4.1
x2ji0402t	1995.018	5.36	0.6	–0.1	0.5	1.1	1.2	2.3
x2ji0602t	1995.155	4.58	–2.9	–0.7	3.8	0.9	2.4	3.3
x2x10105t	1995.279	4.46	0.8	–0.1	0.5	1.3	–2.2	–0.9
x2x10202t	1996.024	5.50	–1.4	–0.1	0.5	–0.9	2.1	1.2
x2x10205t	1996.024	4.48	–1.4	–0.1	0.5	–0.9	1.9	1.0
x2x10302t	1996.156	4.14	2.4	–0.1	0.5	2.9	0.6	3.5
x2x10305t	1996.156	3.60	2.4	–0.1	0.5	2.9	1.5	4.4
x3em010bm	1997.207	4.81	–0.4	–0.2	1.1	0.7	2.1	2.8
x3i00102t	1996.276	2.83	0.6	–0.65	3.5	4.1	0.5	4.6
x3i00105t	1996.276	2.29	0.6	–0.65	3.5	4.1	1.8	5.9
x3i00202p	1997.031	2.56	4.0	–0.2	1.1	5.1	–0.5	4.6
x3i00205p	1997.031	1.58	4.0	–0.2	1.1	5.1	0.3	5.4
x3i00302m	1997.157	4.52	0.1	–0.2	1.1	1.2	0.2	1.4
x3i00305m	1997.157	4.26	0.1	–0.2	1.1	1.2	0.5	1.7
x3tj0205r	1997.084	4.50	1.0	–0.2	1.1	2.1	–0.4	1.7
x4e10102r	1997.300	5.70	–1.3	–0.2	1.1	–0.2	–0.6	–0.8
x4e10105r	1997.300	5.44	–1.3	–0.2	1.1	–0.2	0.6	0.4

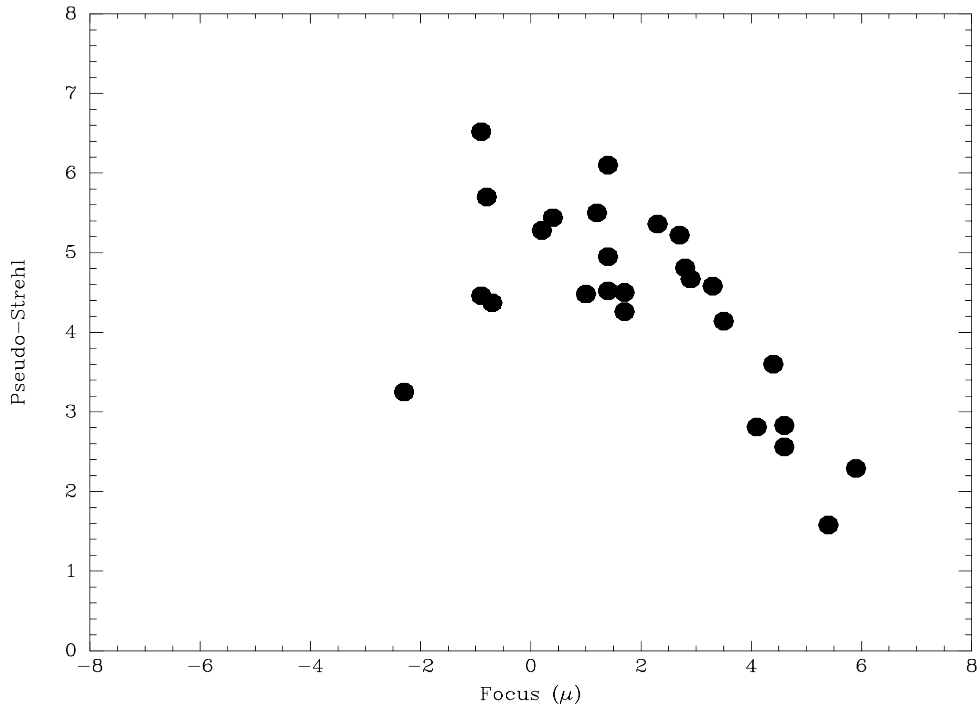

Figure 3: Pseudo-Strehl ratio (fraction of total light in the central pixel) as a function of focus for images taken using the F120M filter.

Table 4: Results of pseudo-Strehl analysis of F278M images

Dataset	Pseudo-Strehl (%)	Date	Focus					
			OTA (μ)	COSTAR (mm)	COSTAR (μ)	Net (μ)	Model Delta (μ)	Overall (μ)
x2ap010lt	10.69	94.084	0.5	0.0	0.0	0.5	0.7	1.2
x2ur0202t	9.86	95.243	1.6	–0.1	+0.5	2.1	–1.6	0.5
x2ur0205t	10.18	95.243	1.6	–0.1	+0.5	2.1	–1.9	0.2
x2ur0402t	6.05	95.336	–0.4	–0.1	+0.5	0.1	–3.4	–3.3
x2ur0405t	9.16	95.336	–0.4	–0.1	+0.5	0.1	–1.4	–1.3
x2ur0602t	10.28	96.020	–1.3	–0.1	+0.5	–0.8	0.8	0.0
x2ur0605t	10.08	96.020	–1.3	–0.1	+0.5	–0.8	1.7	0.9
x2ur0802t	9.90	96.076	3.7	–0.1	+0.5	4.2	–0.3	3.9
x2ur0805t	5.49	96.076	3.7	–0.1	+0.5	4.2	0.5	4.7

Dataset	Pseudo-Strehl (%)	Date	Focus					
			OTA (μ)	COSTAR		Net (μ)	Model Delta (μ)	Overall (μ)
				(mm)	(μ)			
x3cr0205t	2.65	96.191	1.8	–0.65	+3.5	5.3	1.3	6.6
x3cr0402t	9.91	96.338	4.7	–0.2	+1.1	5.8	–0.8	5.0
x3cr0405t	1.77	96.338	4.7	–0.2	+1.1	5.8	1.8	4.0
x3cr0602m	4.48	97.198	–0.3	–0.2	+1.1	0.8	–4.5	–3.7
x3cr0605m	7.23	97.198	–0.3	–0.2	+1.1	0.8	–3.6	–2.8
x3cr0802r	10.51	97.298	–1.2	–0.2	+1.1	–0.1	–0.3	–0.4
x3cr0805r	8.22	97.298	–1.2	–0.2	+1.1	–0.1	–1.2	–1.3
x3tj020ar	13.47	97.084	1.0	–0.2	+1.1	2.1	–0.8	1.3

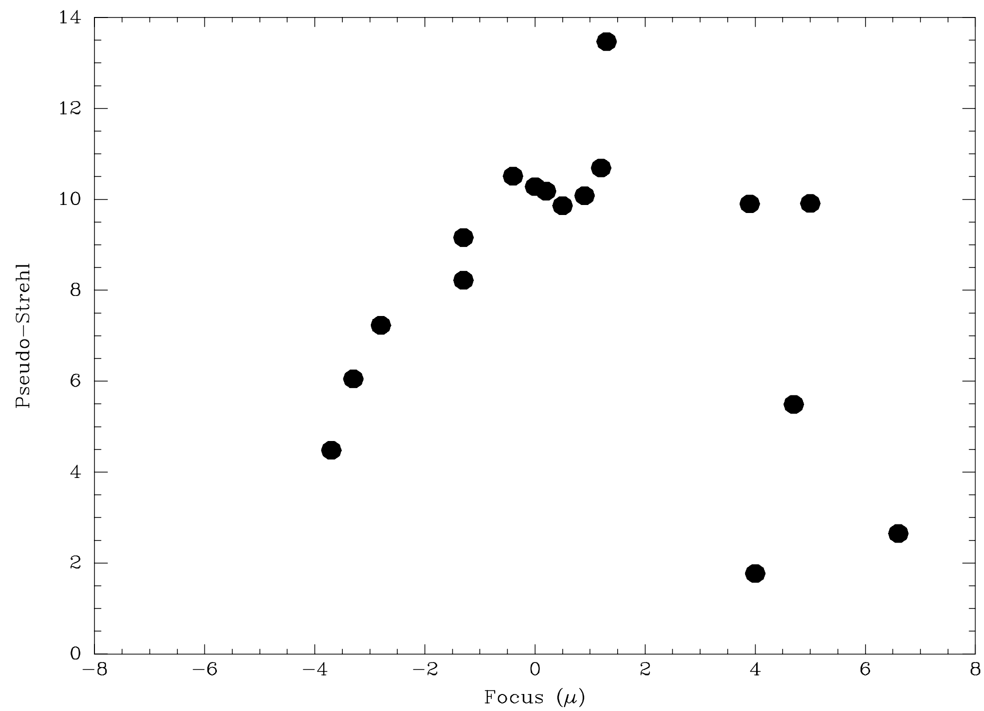

Figure 4: As Figure 3, but for the F278M filter.

Inspection of Figures 3 and 4 show that the optimum focus is at a setting close to zero focus, with a most likely best setting at +1μ. This agrees with the results of the phase retrieval measurements. The scatter in the relation between pseudo-Strehl ratio and focus appears to be good for the F120M measurements, and for the -ve focus measurements using the F278M filter, but is poor for the +ve focus F278M measurements. The reason for this is unknown, but it appears to be real, as evidenced from the data taken on day 96.338. Here, consecutive images taken a little over an hour apart have pseudo-Strehl measurements of 9.9% and 1.8%, a difference clearly visible in the raw data. Clearly there was a significant focus change between the two measurements, but the attitude model was not able to reproduce the change, or even indicate that a large change in focus might have occurred around the time of the observations. Still, for the most part, the predictive focus model does well in reducing the scatter from what would be seen if the raw focus measurements were used in the analysis.

5. Implications for FOC focus

Both phase retrieval of F486N images and pseudo-Strehl analysis of UV images demonstrate that when the COSTAR DOB position is set to -0.2mm, the COSTAR-corrected FOC is confocal with WFPC2. The DOB was set to this position on October 30 1996, and has remained there ever since. This means that since late 1996, the FOC focus has been tracking the WFPC2 focus. Now that the desorption rate appears to have slowed down to only about 0.25μ/month, it is only necessary to compensate for desorption once per year (instead of once every six months as was the case in 1994-1996). In that case, the maximum focus error is only about 1.5μ, which is perfectly adequate for FOC observations. So now **separate adjustments of the COSTAR DOB are not necessary** to keep the FOC in focus.

At the time of writing (January 1998), the focus is drifting negative, and stands at around –2μ. A focus adjustment is planned for early February, at the end of the NIC3 campaign. This will keep the focus for all HST instruments close to optimum for the rest of 1998.

Applying the COSTAR corrections to the WFPC2/OTA focus data (assuming that the COSTAR-corrected FOC is confocal with WFPC2 when the DOB is set to -0.2mm) gives the relation between the nominal FOC focus and time, presented in Figure 5. From this, it can be seen that the error in the nominal focus was less than 2μ for most of 1994 and 1995, but was between 2 and 5μ for most of 1996. The main reason for this was that the slowdown in the OTA desorption rate was not noticed, and so the applied secondary mirror moves were overcorrecting for the WFPC2 focus error in 1996. At the same time, the focus offset between FOC and WFPC2 was not known exactly and FOC observations were not considered reliable enough to allow an independent determination of the focus error.

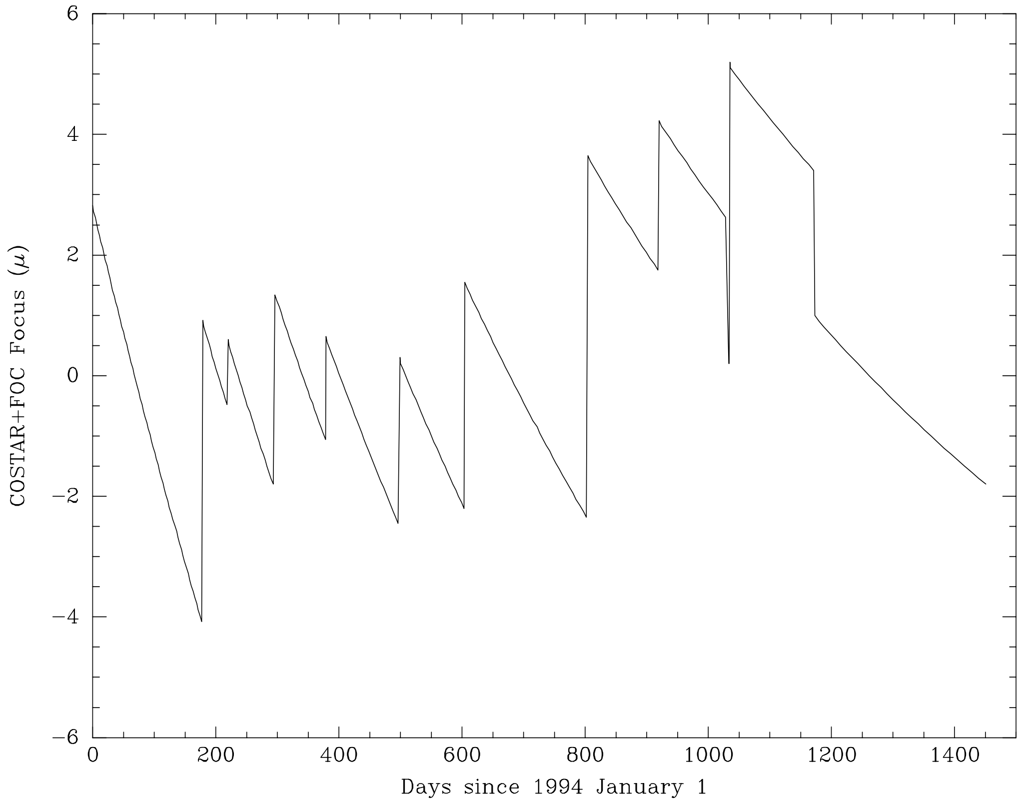

Figure 5: The nominal COSTAR+FOC focus (μ) plotted as a function of time in days since January 1 1994.

The focus for an individual FOC observation can be found by determining the nominal focus for the date of the observation by reference to Figure 5 above, or else by referring to the data in the FOC WWW pages.

6. Conclusions

Data from the PSF monitoring program has been used to show that the COSTAR-corrected FOC focus is different from that of WFPC2 by the equivalent of 1μ of secondary mirror displacement. The current COSTAR setting (–0.2mm) makes the FOC and WFPC2 confocal. Since the WFPC2 focus is kept more tightly controlled than in previous years when the OTA desorption rate was higher, it is no longer necessary to apply separate (and more frequent) COSTAR focus updates to keep the FOC focus acceptable.

The COSTAR+FOC focus was controlled to better than +/-2μ during 1994-5 and 1997, but was between 2 and 5μ in error for most of 1996.