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

FOC Status and Overview

R. Jedrzejewski

Space Telescope Science Institute, Baltimore, MD 21218

Abstract. The calibration status of the Faint Object Camera is described. The best reference files to be used with COSTAR-corrected data are given, along with some discussion of the accuracies to be expected when these files are used. Finally, some discussion of the calibration of polarimetric and objective-prism spectroscopic observations is given.

1. Introduction

The Faint Object Camera is the only one of the original complement of prime science instruments that is still on HST, having been working for over seven years. In that time, our knowledge of the characteristics of the instrument has grown, while at times our understanding has lagged behind. In this paper, the most up-to-date summary of the characteristics of the FOC is given, concentrating on changes from the time of the last Calibration Workshop, in May 1995. This review will concentrate on the F/96 camera only; the F/48 relay will be covered in the next presentation.

2. Calibration Pipeline Overview

The automatic calibration pipeline performs at most four tasks to calibrate FOC data:

1. Dezooming (if the data were taken in zoom mode)
2. Computing photometric parameters
3. Geometric correction
4. Flatfielding

Along with these steps are some capabilities that were originally envisioned as necessary, but have since been found to be either pointless, or else impractical to implement. These are:

1. Background subtraction
2. ITF correction

The former step is not used, since the FOC background defies predictive modelling, and most users can just determine the background locally from the data themselves. The latter step was originally included as a means of correcting nonlinearity (ITF stands for Intensity Transfer Function), but is now being considered as a way to apply a format-dependent flatfield. A review of all FOC calibration products was undertaken in 1994 (Instrument Science Report FOC-082); this paper extends that work to the mid-1997 timeframe.

The currently applied calibration steps are now described in more detail:

2.1. Dezooming

There really isn't much to say about this. No reference files are harmed in performing this step. Each zoomed pixel is merely replaced by two pixels containing half of the zoomed intensity.

2.2. Computing Photometric Parameters

The 5 FOC photometry keywords in the FOC data header are:

1. PHOTMODE—this is the string describing the components that are required to determine the sensitivity
2. PHOTFLAM—this is the computed (by synphot) flux (in erg/cm^2/sec/Å) that gives rise to a total count rate of 1 count/sec (in an aperture of radius 1 arcsecond)
3. PHOTZPT—the ST magnitude zeropoint; this is always -21.10 mag by definition.
4. PHOTPLAM—the pivot wavelength, as defined in Equation 1 below
5. PHOTBW—the rms bandwidth of the filter+detector

The critical parameter is PHOTFLAM. However, users usually don't want to know the flux in ergs/cm^2/sec/Å that gives rise to a unit count rate, they want to know, for example, the V magnitude of a G2V star that gives 1 count/sec total. Fortunately, the STSDAS SYNPHOT package makes this calculation relatively simple:

```
calcphot obsmode=‘‘band(v)’’ \
>>> spectrum="rn(crgrid$bz77/bz_26.tab,band(foc,f/96,costar,f430w),1.0,counts)" \
>>> form="vegamag"
```

will work out the V magnitude for a star from the Bruzual spectral atlas with a G2V spectrum (`bz_26.tab`), renormalized so that the FOC F/96 camera with F430W filter gives 1.0 count/sec. The answer is $V = 22.62$ mag.

The sensitivity is derived by integrating over wavelength the product of the various throughputs and sensitivities in the light path. A typical FOC observing configuration has 7 components, plus 1 for each filter used. For the example given above (F/96, F430W filter), the components are:

Table 1. Components used in deriving FOC sensitivity

Throughput table	Explanation
hst_ota_005.tab	OTA throughput
foc_96_m1m2_001.tab	COSTAR throughput
foc_96_rflpri_002.tab	FOC primary (≡ 1.0)
foc_96_rflsec_002.tab	FOC secondary (≡ 1.0)
foc_96_f430w_002.tab	F430W filter
foc_96_rflfocus_002.tab	FOC refocus mirror (≡ 1.0)
foc_96_n512_001.tab	Format-dependent sensitivity
foc_96_dqe_004.tab	FOC/96 detector sensitivity

The OTA throughput reference file is unlikely to be apdated unless an identical change in performance is noticed by users of all HST instruments. Similarly, the COSTAR throughput is combined with the FOC sensitivity in such a way that there is no point in trying to determine each separately. The FOC primary, secondary and focus mirror terms are set

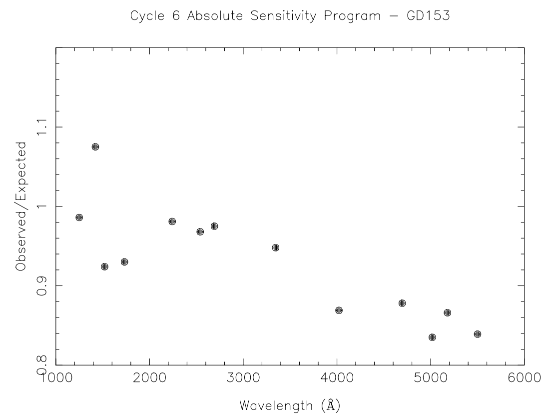

Figure 1. FOC Photometry of the primary standard GD153

to 1.0 and absorbed into the FOC detector sensitivity. The filter transmission curves were determined from ground test measurements, and will not be modified unless an individual filter is found to behave significantly differently from other filters in the same wavelength region.

Thus, the only throughput components that are subject to revision as a result of improved calibration are the FOC detector sensitivity and the format-dependent sensitivity. There are two parts to the calibration; setting the absolute value by observation of standard stars with known flux, and determining any changes in this value. The first must be done by observing a spectrophotometric standard star, while for the second, the only requirement is that the spectrum of the star not vary.

In practice, the calibration of the detector sensitivity has been done by observing spectrophotometric standards. Typically, these are the faintest of the IUE standards (BPM16274 at $V = 14.20$, HZ4 at $V = 14.52$ and LB227 at $V = 15.34$ mag). BPM16274 has absolute IUE flux calibration in the UV, but no visible spectrophotometric calibration. HZ4 and LB227 have both IUE UV spectrophotometry and Oke visible spectrophotometry. Observations during 1994 showed good agreement between the UV measurements of BPM16274 and HZ4 (see Instrument Science Report FOC-085), but 1996 observations of HZ4 showed some disagreement from observations of LB227, at the 10–20% level, while agreeing with the Cycle 4 observations of HZ4. Note that none of the faint standards used have FOS spectroscopy.

To try and overcome the confusion between standards, the 1997 absolute calibration program used the PRIMARY standard GD153 as the target. This white dwarf standard, described in Bohlin et al. (1995), has FOS spectrophotometry that agrees with the model atmosphere prediction to better than 1–2% everywhere, so there is no doubt as to the reliability of the absolute flux levels.

Comparison of the measured count rates with the SYNPHOT predictions showed a surprising trend with wavelength; in the UV, the measured count rates were close to the predictions, with large (∼5%) scatter, while in the visible, the measured count rates were down by 10–15% from the prediction. As can be seen from Figure 1, there is a roughly linear relation between the observed/expected count rates and wavelength.

The observed behavior is not just a reflection of the fact that the previously observed standard stars have larger spectrophotometric errors than the primary standard; it has been noticed that the FOC sensitivity is changing with time. We can rule out significant changes between 1994 and 1995, because monitoring of a standard star with a variety of filters over that timeframe did not show any changes at the 5% level or so. However, later observations (mid-late 1996 and 1997) have shown that the throughput of the FOC is declining slowly, at

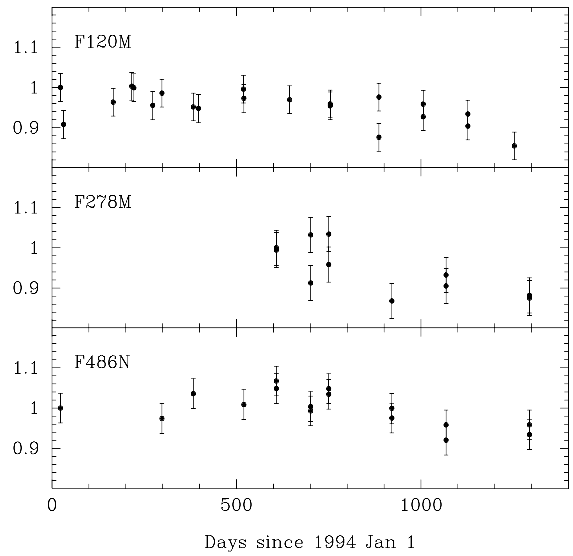

Figure 2. FOC Sensitivity Trends, 1994–1997

approximately 10%/year, with little or no dependence of the sensitivity drop on wavelength. The relative sensitivities of observations in three filters (F120M, F278M and F486N) are plotted in Figure 2.

Observations made just after the Second Servicing Mission (when COSTAR was retracted) showed that the sensitivity drop is confined to the FOC, and not due to any degradation in COSTAR or the OTA. It is not clear at this point whether it is possible to "tune" the FOC to restore this sensitivity. Currently, we are working on trying to characterize this sensitivity drop using all available data. In the meantime, users are advised to assume that the error on the absolute sensitivity can be as large as 15%.

Until the recent sensitivity changes have been characterized reliably, users should use the foc_96_dqe_004.tab instrumental sensitivity file for absolute calibration. This was installed as the default sensitivity file in October 1994, so observations taken before then will have used the earlier file, with possible errors of up to 20–30% in the UV.

2.3. Geometric Correction

The geometric correction for the F/96 camera has been improved by use of images of a crowded field to sample the geometric distortion pattern on a finer scale than is provided by the reseau marks etched onto the photocathode. The method has been used to derive geometric correction files for the 512×1024(z), 512×512, 256×256 and 128×128 formats. For details, consult the Instrument Science Reports FOC-086 and FOC-087.

The optimum geometric correction files are given in Table 2.

On a more global scale, it is known that the overall plate scale and rotation angle of an FOC image change over short timescales; this can be seen by blinking well-exposed images of a diffuse source taken shortly after the camera is switched on. Unfortunately, there is no strong repeatable pattern to the variation. However, plate scale changes are generally limited to ±0.1%, and rotation angle to $\pm0\overset{\circ}{.}1$.

We hope to develop a simple method to apply low-order corrections to the geometric correction files to be used; this will allow more reliable co-addition of multiple images when the geometric distortion changes significantly from image to image. Interested users should keep an eye on the FOC WWW pages.

Table 2. Best Geometric Reference Files for COSTAR-corrected FOC data

Format	Best GEO file
512×512	f371529ex.r5h
512×1024(z)	f371531ox.r5h
256×256	f3715276x.r5h
128×128	f371524px.r5h
512×1024	ga10937nx.r5h
256×1024	f371522ex.r5h

2.4. Flatfielding

The FOC flatfield is mainly the manifestation of photocathode sensitivity variations. These exist on all scales, from the pixel-to-pixel scale to that of the whole detector. However, unlike the case with CCDs, the flatfield response varies only slowly with wavelength. This is fortunate, since the process of acquiring flatfield data of sufficient signal-to-noise is extremely time-consuming. In practice, flatfields have been taken for a few select wavelengths where a suitable celestial target exists (the Orion nebula in the ultraviolet) or else where the internal LED lamps are active (4800–6500Å).

Because of the count-rate limited nature of the FOC, it is not practical to obtain enough counts to provide a signal-to-noise per pixel of 1% or so. When the full 512×1024(z) format is used, the maximum allowable count rate for which the response is still reasonably linear is about 0.03 counts/pixel/s, so to obtain the necessary 10000 counts/pixel would require exposure times of 3×10^5s or so, or over 3 days of continuous illumination. Instead, the flatfields are smoothed over scales of 15 pixels or so to improve the global accuracy, at the expense of fine-scale precision. The geometric distortion is not stable enough to ensure that small-scale features will remain in the same place in the image such that fine-scale flatfielding would work.

Overall, there is not a huge difference between the flatfields from the UV to the visible. Typically, the amplitude of any differences are 10% or so, with an rms variation of 3%. Near the red end of the FOC response (for wavelengths > 5600Å), the global sensitivity variations are somewhat enhanced, but this is an extremely rarely-used wavelength region for the FOC. Similarly, the small-scale features are more pronounced in the ultraviolet.

The best current flatfields were derived from pre-COSTAR flatfields, with the geometric correction adjusted to reflect the difference between the pre-COSTAR and COSTAR-corrected geometric distortion. The best flatfields are given in Table 3 below:

Table 3. Best Flatfield Reference files for COSTAR-corrected FOC data

Wavelength Range (Å)	Best Flatfield
$\lambda < 2555.0$	f3716027x.r2h
$2555 < \lambda < 5184.6$	f3716029x.r2h
$5184.6 < \lambda < 6079.5$	f371602cx.r2h
$\lambda > 6079.5$	f371602dx.r2h

Here the wavelength is the pivot wavelength, defined as

$$\lambda_P(P) = \sqrt{\frac{\int P(\lambda)\lambda d\lambda}{\int P(\lambda)d\lambda/\lambda}} \tag{1}$$

where $P(\lambda)$ is the instrumental sensitivity. These flatfields are the "best" for all COSTAR-corrected data, until superior versions are delivered. Users are advised to check the FOC WWW pages to learn of any new developments in the area of reference files.

The large gap in the wavelength coverage of the flatfields will be closed somewhat with the completion of the Cycle 6 calibration program. Here, images of the Orion nebula will be taken using the F220W filter to provide a near-UV flatfield. Analysis of some of the data which were taken as part of the Cycle 4 calibration program showed small but significant differences from the F140W flatfield that had been acquired before COSTAR was inserted.

Finally, there is a component of the flatfield response that appears to be associated with the TV camera rather than the photocathode. Normally, when the flatfield for a format other than the full 512×1024(z) format is required, the appropriate subsection of the full-format flatfield is used. It has been found that the ratio of a small-format flatfield to the subsection of the full-format flatfield is not constant, with variations of 10–20% or so on the right-hand edge, where the scanning beam starts up. It had been suspected that this was merely a result of the rapidly-changing geometric distortion in that part of the image, and that if the distortion were modelled correctly, the apparent sensitivity variations would disappear. Recent work by Greenfield (FOC Instrument Science Report FOC-086) has shown that this is not the case; even when the improved geometric correction is applied, the sensitivity variations remain. Users should be aware that the sensitivity in the 100-pixel wide region on the right-hand side of the image may be different from that over the rest of the image by up to 10–20%, until this effect is corrected in the FOC pipeline.

3. Expected Accuracies

It is always difficult to try and summarize the performance of the FOC with a table of the accuracies you can expect; one always feels that it is necessary to include disclaimers or "your mileage may vary" warnings. Still, such a table can at least highlight the capabilities of the instrument and warn users away from projects that require precision well beyond that which the FOC can deliver. Table 4 gives a summary of the accuracies you can expect to achieve from FOC observations.

4. Special Modes: Objective Prisms and Polarizers

4.1. Objective Prisms

The F/96 camera has two objective prisms that provide low dispersion spectroscopic capability with high throughput. The calibration of the prisms has been improved recently, and a set of data analysis programs have been incorporated into the STSDAS `focprism` package. The Near-UV prism provides coverage from 1600Å to 6000Å, with a dispersion that goes from about 0.6Å/pixel at 1600Å to 81Å/pixel at 6000Å. Typically, spectrophotometry is possible to approximately 0.1–0.2 mag accuracy, and the wavelength calibration is good to about 1.8Å at 1600Å and 17Å at 2500Å. The red end of the wavelength calibration is less accurate, but a planned Cycle 6 calibration program has been designed to address this. Results will be posted on the FOC WWW pages when they are available.

The Far-UV prism covers all the way down to 1200Å, but the dispersion is very low in the visible. At 1200Å the dispersion is 1.7Å/pixel, but at 5000Å it is more than 500Å/pixel, such that the entire 3000–6000Å range is covered in only 10 pixels in the dispersion direction! Typical spectrophotometric accuracies are again in the 10–20% range, and wavelength uncertainties range from approximately 1.3Å at 1200Å, to $\sim$ 16Å at 1800Å.

Interested parties should refer to FOC Instrument Science Report FOC-092 for more details.

Table 4. Accuracies you can expect from FOC observations

Procedure	Estimated Accuracy	Notes
	Calibration:	
Flat fielding	< 5% rms large scale	
	5–10% rms small scale	"Clean" areas
	Up to 90%	On reseau marks, scratches
Geometric Correction	0.3 pixel rms	
	Relative Photometry	
Repeatability:	∼2–3% rms	As long as statistical errors are not important, target in same place on detector.
Background determination	∼1–2%	Depends on aperture size, but generally not a dominant contributor to overall error
PSF/focus effects, small apertures	Up to 50%	1 pixel aperture, UV wavelengths
PSF/focus effects, large apertures	∼2–3%	Aperture size >10 pixels radius
	Absolute photometry	
Sensitivity	∼10% for most filters	But beware of recent changes
	Astrometry	
Relative	$0\farcs005$ rms	After geometric correction
Absolute	$1''$ rms (estimated)	Guide star uncertainty

4.2. Polarizers

The FOC F/96 camera is equipped with three polarizers with pass directions at 0°, 60° and 120° to the image x axis. They consist of double Rochon prisms cemented together, so that the ordinary rays are transmitted undeviated, while the extraordinary rays are shifted off the detector. The transmission of the pass direction and rejection of the perpendicular polarization are very good, much better than the performance of most polaroids. Also, since most of the reflections in the FOC+COSTAR optics are at small angles of incidence, very little instrumental polarization is induced (<1%).

However, it is not easy to obtain accurate polarization values, especially for point sources. This is partly because the polarizing prisms modify the point-spread function (especially the POL60 prism) in such a way as to introduce an unknown (and uncalibratable) aperture correction to the measured flux whose value does not become unimportant until the aperture radius is as large as 7–10 pixels (0.1–0.15 arcsec).

Secondly, the FOC is not exactly a precision photometric instrument. Repeated observations of the same target through the same filters typically show an rms deviation of 2–3% even when the Poisson noise associated with each observation is 1% or less. The fundamental limit to the accuracy of FOC photometry is believed to be small-scale features in the flatfield, which are not removed in the flatfielding process. (Recall that the flatfields used are heavily smoothed to give adequate signal-to-noise ratio). Acquiring such flatfields would be prohibitive.

To show how the polarization analysis depends critically on the aperture size, Figure 3 shows the apparent degree of polarization for multiple observations of an unpolarized star through the three polarizer filters and the F342W filter. The eight observations (3 in POL0, 2 in POL60 and 3 in POL120) were combined with each other in all possible combinations to give a total of 18 polarization "observations". The PSF was observed to change slightly

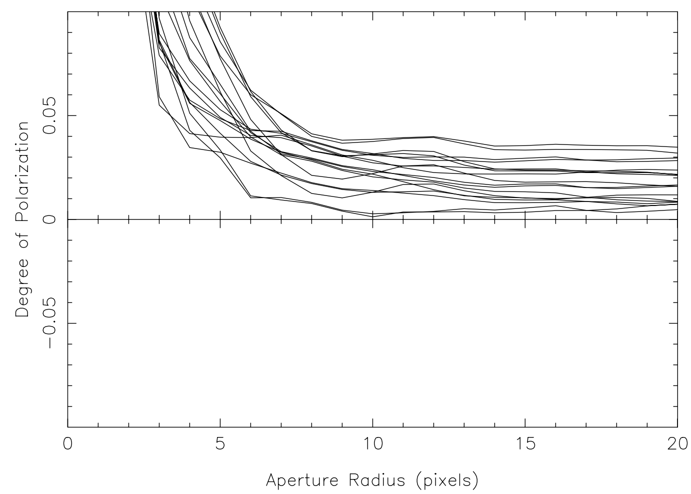

Figure 3. Effect of aperture size on measured point-source polarization

from observation to observation, even for images using the same polarizer, due to small focus effects. It is easy to see that the apparent "polarization" does not settle down to its small value until the aperture radius is 7 pixels or larger. However, users should also note that 7 FOC F/96 pixels correspond to 1 WFC pixel, so the loss in resolution is not too bad.

It can also be seen that the individual observations converge to values between 0 and 3% or so. This is about as well as the polarization can be measured for a well-exposed, isolated point source. Users who are careful to try and overcome some of the sources of systematic error (for example, by dithering between multiple images to lessen the effects of the small-scale flatfields) can, in principle, reach these levels of accuracy. However, a program that simply gathers three images, one in each polarizing filter, is much less likely to be able to achieve this level of accuracy for point sources.

For extended sources, one can do better, since the effects of PSF differences are lessened and the flux is in general averaged over areas that mitigate the influence of the small-scale flatfields. However, here one has the problem of trying to determine the background; extended objects are less likely to have "empty" areas of the image to be used for background determination.

In summary, polarization accuracies of 1–2% are achievable if care is taken in the observations or if extended sources are observed.

Acknowledgments. Many people who have contributed to the continuing success of the FOC. In particular, Perry Greenfield, Warren Hack and Mark Voit and Antonella Nota did much of the analysis reported here.

References

Bohlin, R., et al., 1995, AJ, 110, 1316