8.1 Photometry

The basic strategy for performing photometry on FOC point sources proceeds as follows:

- Choose an appropriate aperture size.
- Measure the counts within the aperture.
- Measure the background flux outside the aperture.
- Assess the fraction of encircled signal within your aperture using an appropriate FOC point spread function (PSF).
- Convert counts to flux using the PHOTFLAM keyword and exposure time.

You can easily do the first three steps with standard IRAF aperture photometry tasks, for example, the phot task in the noao.digiphoto.appphot package. Below we describe how to work with FOC point spread functions, and the section on “Converting Counts to Flux or Magnitude” on page 3-15 shows how to use the PHOTFLAM keyword.
8.1.1 Point Spread Function

Users performing photometry on FOC point sources need to know how to normalize their point-spread functions. In other words, given your particular combination of aperture and background annulus sizes, what fraction of the total flux are you measuring? In order to help you answer this question, a set of observed PSFs is publicly available via the WWW at:

http://www.stsci.edu/ftp/instrument_news/FOC/foc_tools.html#psfs

Alternatively, you can retrieve the PSFs via anonymous FTP from ftp.stsci.edu in the directory:

/instrument_news/FOC/Foc_tools/psfs/psf_files/f96/foc+costar

Once you have selected the appropriate PSF for your observed wavelength, you can apply the very same aperture and background annulus parameters to determine the fraction of the total flux that your technique measures.

The on-line PSF files are in FITS format and have been normalized so that the total background-subtracted flux is 1.0. The total fluxes and backgrounds were measured in exactly the same way as the DQE curve. So, for example, if a particular choice of aperture size and background region returns the result of 0.5 when applied to a PSF file, then 50% of the flux is measured.

Another example may further clarify this procedure. The image x2330106p.png is a 596 second F220W image of a field in the globular cluster 47 Tucanae. The inverse sensitivity for this image, given by the keyword PHOTFLAM in the image header, is $2.017 \times 10^{-17}$. However, as pointed out in “Absolute Sensitivity Correction (WAVCORR)” on page 6-3, the PHOTFLAM values in data taken in the early part of the COSTAR-corrected era were incorrect in that they did not use the COSTAR element in the PHOTMODE string, and the DQE curve used was subsequently superseded by one made using on-orbit measurements. Using synphot to re-evaluate the PHOTFLAM for this mode gives $3.131 \times 10^{-17}$.

Photometry done on a particular star using phot found a total of 631.52 counts with a particular choice of aperture parameters. Using the same choice of parameters on the F220W PSF gives 0.713, or 71.3% of the flux. Thus, the total flux from the star is $631.52 / 0.713 = 885.72$ counts, and the total count rate is $885.72 / 596.0 = 1.486$ counts/sec. The weighted mean flux from the star over the F220W+FOC+OTA+COSTAR passband is then $1.486 \times 3.131 \times 10^{-17} = 4.65 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$.

One troublesome feature of the FOC’s nearly diffraction-limited PSF is that small aberrations can affect the photometry significantly, especially within small apertures. Users should be aware that small, unpredictable, time-dependent focus variations due to thermal effects in the OTA (breathing) can slightly defocus the FOC PSF. The effect on photometry is small for aperture radii larger than 0.1 arcseconds (a few percent at most), but the flux in the central pixel can vary by more than a factor of two from one exposure to the next, especially in the 2000 to 3000 Å range.

Unfortunately, there is no good method to determine the quality of the focus for a particular image, making it very difficult to model the effect of defocusing on
the aperture correction for stellar images. The alternative is to increase the sizes of the error bars to account for this uncertainty in the photometric zero point.

Similarly, there is a small field dependence of the PSF, mainly a focus and astigmatism term. The magnitude of the effect is small over the 512 x 512 imaging format compared to, say, the variations due to breathing. However, again there is no way to model the effect since it presupposes knowledge of the focus of the image at the center of the field.

Overall, users are advised to use an aperture larger than 0.1” radius if accuracy in the zero-point is required to better than 5%. Otherwise, one must expect some uncertainty in the zero point due to aperture correction uncertainties.

As already mentioned in Chapter 4, all pre-COSTAR data are affected by the spherical aberration of the primary mirror. This aberration seriously degraded the FOC PSF, which featured a diffraction limited core (~70 milliarcseconds FWHM) containing 10–15% of the total light of the source, superimposed on a bright diffuse halo. Figure 8.1 shows the aberrated PSF of a spectrophotometric standard star taken with the f/96 and the F140M filter.

Despite the difference between the PSFs obtained with and without the COSTAR correction, exactly the same considerations apply for determining the aperture correction. The difference is that, instead of measuring PSF flux fractions of 50% or higher, most small apertures will only include 5–20% of the flux when applied to pre-COSTAR PSFs. To enclose 50% of the flux required using an aperture size of 0.6 arcsec or so.

8.1.2 Photometric Accuracy
Several factors affect the accuracy of relative and absolute photometry with the FOC.

- **Relative Photometry**: The accuracy to which you can measure the relative fluxes of sources on the same FOC image is dominated by errors in the flatfielding and is expected theoretically to be of the order of 3–5% for sources that do not fall on recognizable image defects (see “Commonly Observed Features” on page 4-7). Empirical determinations of photometric accuracy show that repeatabilities of 3–4% are typical for isolated bright stars where crowding is not important and the total detected flux is more than about 3000 counts. However, tests of photometric accuracy in crowded fields suggest relative errors of about 5% for f/96 and 10% for f/48.

Users should bear in mind that there are no systematic, detailed studies of relative photometry with the FOC, so these estimates of the rms repeatability are somewhat anecdotal.
• **Absolute Photometry**: The absolute photometric calibration of FOC f/96 images was derived empirically by comparing observed and predicted count rates for the spectrophotometric standard stars HZ4 and BPM 16274 (see *FOC ISR 085*). The predicted count rates were calculated using *synphot* from the pre-servicing mission FOC DQE curve, modified to include ground measurements of the COSTAR reflectivity. The observed count rates were measured by summing the flux within an aperture of 70 pixels (1 arcsecond) radius, accounting for the background measured also at 1 arcsecond radius. Note that this procedure is different from the pre-COSTAR case, where a 3 arcsecond radius aperture was used. The measured relation between observed and expected measurements and wavelength was found to be linear, and this linear relation was used to modify the FOC DQE curve. The scatter of the observed and expected measurements using the corrected FOC DQE curve was approximately 8% rms.

Figure 8.1: Pre-COSTAR Image of a Star Taken with f/96 Relay and F140M Filter,
The absolute sensitivity of the f/48 camera has been calibrated only under conditions of very poor instrument performance (high background), so all f/48 fluxes must be considered much more uncertain. Typical uncertainties are of the order of +/- 30%.

Users must also account for the error sources discussed in the previous chapter. In addition to the 10–20% scatter in the absolute calibration accuracy of the f/96 camera (and the considerably higher uncertainty in the f/48 fluxes), there are several effects that can systematically shift the photometric scale for FOC data and go uncorrected in pipeline processing. These error sources, which should be corrected if possible, include:

- Format dependence of the FOC sensitivities (see page 7-10).
- The effect of the source spectrum on the calculated flux (see page 7-15).
- Flatfielding inaccuracies (see page 7-5 and below)

**Accuracy of Flatfielding**

Chapter 7 discusses the sources of FOC flatfielding errors at length. Here we summarize their effects on photometric accuracy. The only component of flatfield response currently corrected in the pipeline is that for large-scale variations because the flatfields used have been heavily smoothed. The reasons for the lack of further corrections are as follows:

- Because of the FOC’s limited dynamic range, obtaining high signal-to-noise flatfields consumes large numbers of HST orbits. Therefore most flatfields have only a few hundred counts per pixel with a corresponding signal to noise of on the order of 5% per pixel from photon noise alone.
- Small drifts in geometric distortion will shift many of the fine scale scratches and blemishes so that they are no longer aligned with those in the flatfield, producing worse flatfielding results around such features.
- The intensity of scratches and blemishes varies considerably with wavelength in the UV. Because there is a UV flatfield at only one wavelength, its scratches and blemishes will be of the wrong depth for most other images.
- Pattern noise and many of the other fine defects in FOC images are not stable and will not be properly removed.

The resulting accuracy of relative photometry is largely governed by the small scale defects, scan rate oscillations, the intrinsic error in the large scale flatfield, and changes in the flatfield that depend on wavelength. This last error is probably on the order of 2–4% rms (this and subsequent discussions of errors apply to the area of the photocathode more than about 100 pixels away from the edges and corners of the format). Given the intrinsic error in the large scale flatfields, the observer should not expect the net large scale accuracy to be better than 3–5%. Some recent checks on photometric consistency of stars in a crowded field have had actual errors closer to 7%.

Errors due to scan rate variations may be as high as 10–20% (peak). Fortunately these errors are usually confined to the first 100 pixels or so of the scan line. Fine scale features such as reseau marks, scratches, blemishes, and video defects can result in much higher errors for the affected pixels. The best
data-analysis advice regarding these problems is to avoid placing targets near these defects in the first place! It is possible to flatfield out scratches and blemishes with the appropriate registration of the flatfield with the science image. To obtain the UV flatfield, contact the STScI help desk (help@stsci.edu). You should keep in mind, however, that no simple offset is likely to register the flatfield with the science image everywhere in the image. Such efforts are easier if you need to correct scratches and blemishes only in a limited area. Furthermore, if the effective wavelength of the target in the science image is much different from that of the flatfield, the scratches and blemishes may not have the same intensity and may not be flatfielded properly.

Pattern noise can produce fluctuations as large as 10% in some pixels (for $f/96$). Fortunately, most analysis techniques average over at least a few pixels, and because the spatial frequencies of these patterns are high, integration over a sizeable aperture reduces their effect significantly. However, they can seriously affect certain image restoration techniques.

### 8.2 Astrometry

The astrometric accuracy of FOC data depends on two factors. The first is the pointing accuracy of the FOC. The second is the internal geometric accuracy of an FOC image itself, including the correctness of the distortion model, the plate scale, and the image rotation.

- **Pointing Accuracy**: Positional errors in the HST Guide Star Catalog contribute most of the error in the RA and Dec assigned to the center of an FOC image. Typical 1σ errors in guide-star positions are $+/- 0.33$ arcsec in the northern hemisphere and $+/- 0.5$ arcsec in the south. One might expect that the (unknown) proper motions of guide stars in this catalog gradually add to these errors. The accuracy with which HST places a target in the FOC field of view depends in a complex way on the target coordinate uncertainty, the positions of the guide stars in the FGS fields of view, and the alignment of the FOC imaging aperture with respect to the FGS reference frame. This FOC-to-FGS alignment is maintained to better than 0.2”, and experience with the overall pointing accuracy of the FOC when GASP coordinates are used has shown that 1 sigma error in the absolute pointing is approximately 0.5 arcsecond.

On top of these errors, different filters induce different target shifts within FOC images (Table 8.1 lists known filter shifts). In most cases, the translation of the image due to the filter is small (1–3 pixels, or 0.015–0.05 arcsec), but some filters do introduce a large shift. Particularly notable are the F320W (shift=88 pixels) and F486N (shift=20 pixels) filters.

- **Relative Positions**: The best estimate of the accuracy of the relative positions within an FOC image comes from the rms residuals of star positions in the crowded field used for calibrating the geometric distortion. Typical values are 0.3 pixels (0.005 arcsec) for the 512 (zoomed) x 1024 format and
0.2 pixels (0.003 arcsec) for the 512 x 512 format. These uncertainties are compounded by the uncertainty in the plate scale, which is subject to time variation.

The absolute calibration of the plate scale and rotation has been accomplished in two ways; firstly, by observations of an astrometric star field using astrometric guide stars, and secondly by using the programmed offsets between observations in the crowded-field geometric distortion analysis. Typically, these different measurement methods give consistent results in cases where the pointing system operates without anomalies. However, the FOC plate scale can vary from switch-on to switch-on. Comparisons of images of the same field taken several months apart have shown plate-scale variations as large as 0.7%. These time-dependent drifts of the FOC plate scale have never been studied in any systematic way.

Based on all the above, the best estimate for the f/96 plate scale is:

\[
\text{f/96 plate scale} = 0.01435 \pm 0.00007 \text{ arcseconds/pixel}
\]

Recent measurements of the f/48 plate scale which compare images of the same crowded field from both the f/48 and f/96 cameras show that the plate scale of the f/48 is:

\[
\text{f/48 plate scale} = 0.02870 \pm 0.00029 \text{ arcseconds/pixel}.
\]

The best estimates for the pre-COSTAR f/96 and f/48 plate scales are:

\[
\begin{align*}
\text{f/96 plate scale} &= 0.02217 \pm 0.00010 \text{ arcseconds/pixel} \\
\text{f/48 plate scale} &= 0.04514 \pm 0.00012 \text{ arcseconds/pixel}.
\end{align*}
\]

### 8.3 Polarimetry

The f/96 camera of the FOC contains three linearly polarizing prisms with names POL0, POL60, and POL120. The E-vector pass directions of these prisms are 0 degrees, 60 degrees, and 120 degrees respectively, counterclockwise from the image x axis (–S direction), as projected onto the sky. The prisms are birefringent beam splitters that transmit one mode of polarization straight through, while deflecting the orthogonal mode so that it misses the central 512 x 512 region of the photocathode.

The pipeline calibration for polarization observations is no different than for other images. That is, no special correction for polarization is applied, and the images are not combined to form Stokes parameter images.

A polarimeter based on three separate polarizers cannot be expected to yield extremely accurate results. One difficulty is that the throughputs of the three polarizers are not identical, and these differences in throughput depend on wavelength. While the filter transmissions have been measured on the ground, filters do change with time, and color variations in the source will result in small differences in the observed throughput. Variations of order one percent exist throughout the visual wavelength range, but the major difference is that the short-wavelength cutoff of POL60 occurs about 500 Å longward of the cutoff of
POL0 and POL120. This divergence begins at about 3000 Å. Tasks in the synphot package can be used to determine the expected throughputs of each of the polarizers together with other filters used for your observations. You can then divide each of the three images by the expected throughput to correct for this difference.

Another limitation of FOC polarimetry is that the incoming light reflects off several mirrors at oblique angles, ranging from a few degrees up to about 11.5 degrees. An oblique reflection at 11.5° off aluminum induces a linear polarization of about 0.2%, incident unpolarized light, and it also results in a phase shift of about one degree. Such a phase shift is insignificant for incident linearly polarized light. If the incident light were 100% circularly polarized, however, a one-degree phase shift would induce a spurious linear polarization of nearly two percent, which would be significant.

Introducing a polarizer into the beam shifts the image by several pixels. The amount of this shift must be known in order to determine the Stokes parameters from the three images. The shifts at various wavelengths are shown in Table 8.1. These values were based primarily on observations with the F346M filter and an objective prism, but observations with F220W and F140W were also used. The wavelength dependence is then derived from the dispersion curve of the far-UV objective prism (FUVOP). With POL0 or POL120 these values are believed to be good to 0.1 or 0.2 pixel, but with POL60 the uncertainty is more like half a pixel because the observations were of lower quality.

Table 8.1: Image Shifts at Various Wavelengths

<table>
<thead>
<tr>
<th>Wavelength (Å)</th>
<th>POL0</th>
<th>POL60</th>
<th>POL120</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
<td>x</td>
</tr>
<tr>
<td>2500</td>
<td>1.4</td>
<td>-7.3</td>
<td>-2.3</td>
</tr>
<tr>
<td>3000</td>
<td>1.3</td>
<td>-7.1</td>
<td>-2.2</td>
</tr>
<tr>
<td>3500</td>
<td>1.3</td>
<td>-7.0</td>
<td>-2.2</td>
</tr>
<tr>
<td>4000</td>
<td>1.3</td>
<td>-6.9</td>
<td>-2.2</td>
</tr>
<tr>
<td>4500</td>
<td>1.3</td>
<td>-6.9</td>
<td>-2.2</td>
</tr>
<tr>
<td>5000</td>
<td>1.3</td>
<td>-6.9</td>
<td>-2.2</td>
</tr>
<tr>
<td>5500</td>
<td>1.3</td>
<td>-6.8</td>
<td>-2.2</td>
</tr>
<tr>
<td>6000</td>
<td>1.3</td>
<td>-6.8</td>
<td>-2.1</td>
</tr>
</tbody>
</table>

The image quality of the FOC suffers somewhat when a polarizing prism is used. While POL0 and POL120 are not bad, and POL60 seems to be good in the visual and blue range, the optical quality of POL60 deteriorates substantially at the shortest wavelengths that the polarizer passes, around 2200 Å. However, polarization observations at wavelengths shortward of about 3000 Å will be very difficult anyway because of the UV transmission cutoff of POL60.
After correcting for these unequal throughputs and shifting the images to register them, you can compute the Stokes parameters \((I, Q, U)\) by simple arithmetic using the \texttt{imcalc} task. Using the \texttt{imcalc} notation \texttt{im1}, \texttt{im2}, and \texttt{im3} to represent the images taken through the polarizers POL0, POL60, and POL120 respectively, the Stokes parameters are as follows:

\[
I = \frac{2}{3} \times (im1 + im2 + im3)
\]

\[
U = \frac{2}{\sqrt{3}} \times (im3 - im2)
\]

\[
Q = \frac{2}{3} \times (2 \times im1 - im2 - im3)
\]

These values can be converted to the degree of polarization \(P\) and the polarization angle \(\theta\), measured counterclockwise from the \(x\) axis as follows:

\[
P = \sqrt{Q^2 + U^2} / I
\]

\[
\theta = \frac{1}{2} \tan^{-1} \left( \frac{P}{Q} \right)
\]

The polarization errors arising from Poisson noise when \(N\) counts have been gathered in the three polarization image are given by:

\[
\sigma_P = \frac{\sqrt{2}}{\sqrt{N}}
\]

\[
\sigma_\theta = \frac{\sigma_P}{2P}
\]

Even for very large \(N\) (i.e. very good signal-to-noise), polarizations of point sources as low as 1–2\% are very difficult to detect reliably because the limiting photometric accuracy of the FOC itself is close to this level. Uncertainties in flatfielding, filter transmission uncertainties, PSF differences between polarizers and other effects will conspire to thwart any attempts to measure polarizations to very high accuracy unless great care is taken to try and minimize the instrumental effects (e.g. by dithering the images, dividing into shorter exposures to investigate PSF changes and differences). Flatfield uncertainties and PSF dependences are less of a factor when analyzing extended sources (with sizes larger than 15 pixels or so), so polarization accuracies of 1\% or so are probably achievable for extended sources.
8.4 Objective-Prism Spectroscopy

The FOC objective prism facility consists of a far-UV prism and a near-UV prism for both the f/96 and f/48 cameras. The far-UV prism (FUVOP) operates down to 1150 Å with a wavelength dispersion \( \lambda / \Delta \lambda \) of around 50. The near-UV prism (NUVOP) transmits only above 1600 Å with a wavelength dispersion \( \lambda / \Delta \lambda \) around 100 at 2500 Å. Both the FUVOP and the NUVOP disperse the beam in a direction roughly parallel to the decreasing line number direction with angles of approximately 8 degrees and 11 degrees from the –L direction respectively. This dispersion angle can be seen clearly in Figures 8.2 and 8.3 which show f/96 images taken with the FUVOP and the NUVOP respectively. In the NUVOP image, the feature cutting across the spectrum near the top of the image is a blemish in the camera and not an feature in the source.
Figure 8.2: Composite f/96 Image of Undispersed Star and FUVOP Image
The most recently determined dispersion curves for the $f/96$ objective prisms are given in Table 8.2 along with the available $f/48$ dispersion curves. The wavelengths determined from objective prism spectra using these dispersion curves should have a $\Delta\lambda/\lambda$ error of $<1\%$ for $f/96$ spectra. The $f/48$ dispersion curves are based on pre-launch measurements, so their accuracies are uncertain.
The spectral features in Figures 8.2 and 8.3 have been labeled to illustrate the non-linear wavelength dispersion of the prisms.

### Table 8.2: FOC Dispersion Curves

<table>
<thead>
<tr>
<th></th>
<th><strong>f/96 FUVOP</strong></th>
<th></th>
<th><strong>f/96 NUVOP</strong></th>
<th></th>
<th><strong>f/48 FUVOP</strong></th>
<th></th>
<th><strong>f/48 NUVOP</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>λ(Å)</td>
<td>Offset</td>
<td>λ(Å)</td>
<td>Offset</td>
<td>λ(Å)</td>
<td>Offset</td>
<td>λ(Å)</td>
<td>Offset</td>
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<tr>
<td>1150</td>
<td>-449.2</td>
<td>1600</td>
<td>-570.1</td>
<td>1100</td>
<td>-248.0</td>
<td>1600</td>
<td>-136.0</td>
</tr>
<tr>
<td>1200</td>
<td>-416.0</td>
<td>1700</td>
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<td>1200</td>
<td>-219.0</td>
<td>1700</td>
<td>-109.6</td>
</tr>
<tr>
<td>1300</td>
<td>-369.1</td>
<td>1900</td>
<td>-233.4</td>
<td>1300</td>
<td>-189.8</td>
<td>1850</td>
<td>-70.0</td>
</tr>
<tr>
<td>1400</td>
<td>-339.2</td>
<td>2100</td>
<td>-122.0</td>
<td>1500</td>
<td>-164.9</td>
<td>1900</td>
<td>-56.8</td>
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<tr>
<td>1600</td>
<td>-306.1</td>
<td>2300</td>
<td>-52.7</td>
<td>1700</td>
<td>-154.0</td>
<td>2000</td>
<td>-36.8</td>
</tr>
<tr>
<td>1800</td>
<td>-289.6</td>
<td>2500</td>
<td>-6.3</td>
<td>1900</td>
<td>-147.7</td>
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<td>-20.0</td>
</tr>
<tr>
<td>2000</td>
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<td>2700</td>
<td>27.0</td>
<td>2100</td>
<td>-143.5</td>
<td>2500</td>
<td>-1.2</td>
</tr>
<tr>
<td>2200</td>
<td>-272.7</td>
<td>2800</td>
<td>40.4</td>
<td>2500</td>
<td>-138.3</td>
<td>2700</td>
<td>6.13</td>
</tr>
<tr>
<td>2500</td>
<td>-265.1</td>
<td>3000</td>
<td>62.4</td>
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</tr>
<tr>
<td>3000</td>
<td>-257.8</td>
<td>3200</td>
<td>79.6</td>
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<td>3500</td>
<td>23.6</td>
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<tr>
<td>4000</td>
<td>-251.5</td>
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<td>93.2</td>
<td>4000</td>
<td>-131.6</td>
<td>4000</td>
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<tr>
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<td>-249.3</td>
<td>4000</td>
<td>120.9</td>
<td>5000</td>
<td>-130.4</td>
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<td>6000</td>
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<td>6000</td>
<td>158.5</td>
<td>10000</td>
<td>-126.4</td>
<td>10000</td>
<td>65.2</td>
</tr>
</tbody>
</table>

Figure 8.2 shows that f/96 FUVOP spectra are only about 175 pixels in length at most, while Figure 8.3 shows that NUVOP spectra are over 650 pixels long. Spectra in typical f/48 objective prism images are roughly one half the length of their f/96 counterparts. The small PSF cores, only about 3 pixels FWHM, produce only minimal wavelength contamination along the spectra, except in heavily exposed regions of the spectrum, resulting in well-resolved emission lines. The objective prisms can also be used in conjunction with a variety of other filters to isolate particular regions of interest in a source’s spectrum.

Several STSDAS tasks have been developed for reduction of FOC objective-prism spectra. These tasks are available as part of the STSDAS foc.foc prism package but first require the extraction of the spectrum from the image, a procedure handled especially well by the apall task in the noao.twodspec package. (FOC ISR 092 provides a tutorial.) Once a one-dimensional version of the spectrum has been extracted from the image, the tasks in the foc.foc prism package can be used to convert it into flux units.

The task objcalib in the foc.foc prism package uses routines provided by the FOC Instrument Development Team (IDT) to reduce the spectra extracted from objective prism images. It first takes the extracted one-dimensional spectrum given as counts vs. pixels (as produced by apall) and applies a dispersion curve to
produce counts vs. wavelength. This step depends on having a reliable dispersion
curve to resample the spectrum properly. The task then resamples the spectrum
into wavelength bins, and applies a photometric conversion based on the
observing mode to convert the counts to physical units ergs cm\(^{-2}\) sec\(^{-1}\) Å\(^{-1}\).

Accurate conversion of the observed counts into flux units relies on knowing
the fraction of total emission extracted from the image. Several observations of
spectrophotometric standard stars were used to determine this percentage for
several given extraction widths, with the results given in Table 8.3. This factor is
used to calculate the total flux observed in the spectrum in units of ergs cm\(^{-2}\) sec\(^{-1}\) Å\(^{-1}\). The 3\(\sigma\) errors in the determination of these percentages are also provided as a
guide to the expected errors in the resultant photometry. This method assumes that
the percentage of light counted in each pixel is the same along the spectrum.
Unfortunately, PSFs vary considerably from one end of the spectrum to the other,
possibly introducing errors on the order of 10% in the photometry of the spectrum
at any given wavelength for \(f/96\) spectra. These errors arise from the differences in
the encircled energy from one end of the spectrum to the other.

**Table 8.3:** Photometry for Different Extraction Widths from Objective Prism
Spectra (given as a percent of total detected light in the spectrum)

<table>
<thead>
<tr>
<th>Extraction Width (pixels)</th>
<th>NUVOP</th>
<th>FUVOP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\varepsilon) (%)</td>
<td>(3\sigma) error</td>
</tr>
<tr>
<td>5</td>
<td>55.4</td>
<td>7.4</td>
</tr>
<tr>
<td>7</td>
<td>62.7</td>
<td>6.9</td>
</tr>
<tr>
<td>9</td>
<td>68.0</td>
<td>6.5</td>
</tr>
<tr>
<td>11</td>
<td>72.0</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Overall, photometry of objective prism spectra should have errors of about
10% or less for wavelengths below 4000Å for NUVOP spectra and below 2500Å
for FUVOP spectra, provided that the position of the undispersed target is known
to within a pixel.

### 8.5 Long-Slit Spectroscopy

The \(f/48\) camera of the FOC is equipped with a long-slit spectroscopy facility.
Its entrance aperture has a 0.063 x 12.5 arcsecond slit that can be placed at the
OTA tangential focus as shown in Figure 9 of the *FOC Instrument Handbook,
version 7.0*. The effective wavelength range of this device in first order is
3600–5400Å, in second 1800–2700Å, in third 1200–1800Å, and in fourth
900–1350Å. The MgF\(_2\) window of the detector limits this last range to
1150–1350Å. The linear dispersion at the photocathode is 71, 36, 24, and 18 Å
mm\(^{-1}\) for the respective orders, and the FOC spectrograph resolution is limited by
the slit size and the OTA point spread function to about two to three 24 micron
pixels. Using the Rayleigh resolution criterion, the actual resolving power of the instrument is ~1150 in all orders, yielding spectral resolutions of 4, 2, 1.3, and 1 Å for first, second, third, and fourth orders respectively.

8.5.1 Tribulations of the f/48 Spectrograph

Because of HST’s spherical aberration, the long-slit facility was rarely used before COSTAR. In addition, a failure of the f/48 camera occurred in September 1992. The high voltage tripped while ramping up at the beginning of an observing sequence. For several years thereafter, the background in the f/48 camera was extremely high. As a consequence, the f/48 was unavailable to GOs during Cycles 4 and 5 while tests were carried out to establish its performance and operational reliability.

After a long period of inactivity, the f/48 was switched on again in November 1994, for the first time after the COSTAR deployment. Images and spectra of an extended target were successfully obtained, although they contained two zones of particularly high background that faded with time, a region in the center known as the flare and an arc across the top. The locations of these features can be seen in Figure 8.4, where the images from this observing sequence are displayed with the same intensity contrast to allow direct visual comparison. Because the background had finally decreased to manageable levels, the f/48 camera was made available to observers in Cycles 6 and 7, limited to long slit spectroscopy only. Since then, the prominence of the arc and flare have continued to diminish.

Figure 8.4: Mosaic of f/48 Images from the November 1994 Test. Time since Switch-on increases from left to right.
8.5.2 Reduction of f/48 Spectra

FOC long-slit spectra that have undergone geometric correction and wavelength calibration can be reduced with any IRAF task suitable for two-dimensional spectra, such as the `apall` task in the `noao.twodspec.apextract` package. The standard geometric correction procedure remaps the image so that the spectral dispersion runs directly along the y axis and the spatial dimension runs along the x axis. Corrected spectra have a dispersion of 1.7 Å pixel$^{-1}$, shifted so that 5300 Å corresponds to y pixel 200. Calibration files that simultaneously correct distortion and calibrate the wavelength scale for the 512 zoomed x 1024, 512 x 1024, and 256 x 1024 formats are available through the STScI help desk (help@stsci.edu).

Because the standard geometric correction and wavelength calibration procedure does not account for temporal changes in the distortion of the f/48 camera, we recommend that you create your own custom geometric correction files, if contemporaneous f/48 flatfield observations are available. These internal flatfield images display the reseau marks that trace the geometry of the detector. The transformation that maps these marks to the fiducial positions they would have in a properly corrected image also transforms a contemporaneous raw spectral image into a geometrically-corrected, wavelength-calibrated spectral image. FOC ISRs 096 and 097 describe how to generate custom geometric correction files.

The standard spectrophotometric calibration (SDE) file for f/48 spectral images presumes that the target is centered in the 0.06” slit, an assumption that is not always valid. Multiplying your geometrically corrected image by the appropriate SDE file for the observing format will convert counts to erg cm$^{-2}$ Å$^{-1}$, correcting for the vignetting of the slit as described in FOC Instrument Science Report 098. Integrating the spectrum over the spatial dimension and dividing by the exposure time would then yield a spectrophotometrically calibrated spectrum of a centered point source. To obtain calibrated spectra of extended sources, you will need to multiply by an additional factor of 0.6, because the standard calibration algorithm, geared towards centered point sources, assumes that only 60% of the PSF falls onto the slit.

8.5.3 Accuracy of f/48 Spectroscopy

A calibration program performed in support of the post-COSTAR f/48 spectroscopic observations has determined the slit position, geometric distortion, wavelength scale, and spectrophotometric sensitivity of the spectroscopic facility.

- **Slit Position**: FOC long-slit spectroscopy requires an interactive acquisition, and the position of the slit relative to the target position in an acquisition image is now known to better than 0.1”. However, not all spectroscopic targets in the Archive have been perfectly centered on the slit. It is difficult to tell whether a target is centered in an individual spectroscopic image. If the image is part of a series that scans the slit across the target, you can evaluate the location of the target relative to the slit by measuring how the overall spectral intensity varies from image to image.
Otherwise, you can reconstruct, in principle, the relative positions of the target and the slit from the interactive acquisition image, the slew information in the OCX file, and the geometric distortion model of the f/48 camera. However, no systematic procedure exists for performing this reconstruction.

- **Geometric Distortion:** The geometric corrections for the f/48 imaging mode and the f/48 spectrographic mode have been determined separately. The distortion model for the imaging mode used for interactive acquisitions relies on the same crowded-field technique as the f/96 model. This correction, described in FOC Instrument Science Report 095, rectifies the imaging format to 0.5 pixels rms.

- **Wavelength Calibration:** Long-slit observations of the planetary nebula NGC 6543 form the basis of the geometric correction and wavelength calibration of the f/48 spectrographic mode (see FOC Instrument Science Reports 096 and 097.) The resulting transformation rectifies the spectra so that the dispersion direction aligns to within 0.2 degrees of the image y axis and the wavelength scale remains stable to within 0.5 Å across the x axis. Observers should bear in mind, however, that the geometric distortion of the f/48 camera is time-dependent at somewhat less than the 1% level, so custom geometric corrections are necessary to achieve these accuracies.

- **Spectrophotometric Calibration:** Above and beyond the difficult-to-measure uncertainties stemming from the placement of the target on the tiny FOC slit, there are other uncertainties with f/48 spectrophotometry. Dwell scans of the spectrophotometric standard star LDS 749B, taken as part of the f/48 calibration program, yielded one image in which the target fell directly in the center of the slit. The calibration of the FOC’s spectrographic throughput rests on this one observation. Comparisons of the resulting sensitivity with the predictions from synphot show that the f/48 spectrograph is 10% more sensitive than expected at 4000 Å and about 50% less sensitive than expected at 5000 Å. We estimate that these direct sensitivity measurements are correct to about 20%.

Similar observations of LDS 749B at other scan positions show that the throughput drops by half at an offset of 0.04 arcsec and by 80% at an offset of 0.08 arcsec, so inaccuracies in the target position are likely to be the greatest source of spectrophotometric uncertainty. Furthermore, the wavelength dependence of the off-center throughputs is rather unexpected, being higher in the blue than in the red (see FOC Instrument Science Report 098 for more details.)

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8.6 Summary of FOC Accuracies

The following table summarizes the kinds of accuracies you can expect when analyzing FOC data. Note that many of these numbers come with qualifications and that you should check the relevant sections of this handbook for details.
Table 8.4: Final Accuracies Expected in FOC Observations

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Estimated Accuracy</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Calibration (flatfielding)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flatfielding</td>
<td>&lt;5% rms large scale</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-10% rms small scale</td>
<td>“Clean” areas</td>
</tr>
<tr>
<td></td>
<td>Up to 90%</td>
<td>On reseau marks, scratches</td>
</tr>
<tr>
<td>Geometric Correction - f/96</td>
<td>0.3 pixel rms</td>
<td></td>
</tr>
<tr>
<td>Geometric Correction - f/48</td>
<td>0.5 pixel rms</td>
<td>Full format, central area only.</td>
</tr>
<tr>
<td><strong>Relative photometry (f/96 only)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repeatability:</td>
<td>~2-3% rms</td>
<td>As long as statistical errors are not important, target in same place on detector.</td>
</tr>
<tr>
<td>Background determination</td>
<td>~1-2%</td>
<td>Depends on aperture size, but generally not a dominant contributor to overall error.</td>
</tr>
<tr>
<td>PSF/focus effects, small apertures</td>
<td>Up to 50%</td>
<td>1 pixel aperture, UV wavelengths.</td>
</tr>
<tr>
<td>PSF/focus effects, large apertures</td>
<td>~2-3%</td>
<td>Aperture size &gt;10 pixels radius</td>
</tr>
<tr>
<td><strong>Absolute photometry</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity - f/96</td>
<td>~6% rms for most filters</td>
<td></td>
</tr>
<tr>
<td></td>
<td>~10% rms for uncalibrated filters</td>
<td></td>
</tr>
<tr>
<td>Sensitivity - f/48</td>
<td>~30% for most filters</td>
<td></td>
</tr>
<tr>
<td><strong>Astrometry</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative</td>
<td>0.005&quot; rms (after geometric correction)</td>
<td></td>
</tr>
<tr>
<td>Absolute</td>
<td>1&quot; rms (estimated)</td>
<td></td>
</tr>
<tr>
<td><strong>Spectroscopy (f/48 only)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength Calibration</td>
<td>~0.5-1 Angstrom rms</td>
<td>First order only - higher orders not calibrated.</td>
</tr>
<tr>
<td>Spectrophotometry</td>
<td>~10% rms</td>
<td>First order</td>
</tr>
<tr>
<td></td>
<td>~30% rms</td>
<td>Higher orders</td>
</tr>
</tbody>
</table>