

PART II:

FOC

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■ FOC

FOC Instrument Overview

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The Faint Object Camera (FOC), designed and built by the European Space Agency, is the highest-resolution imaging instrument on the Hubble Space Telescope (HST). It is a long focal-ratio, photon-counting imager operating in the 1150 to 6500 Å wavelength range with a 14 x 14 arcsecond field of view. The Corrective Optics Space Telescope Axial Replacement (COSTAR), installed during the December 1993 servicing mission, restored the two prime scientific objectives of the FOC—deep imagery and photometry of very faint celestial objects and imagery of bright objects at the highest possible resolution—which were hampered by the spherical aberration of the telescope's primary mirror. The corrected FOC offers imaging capabilities with a pixel size of 0.014" and a FWHM of 2–3 pixels, providing peak sensitivity at 3400 Å. Low detector background and insensitivity to cosmic rays allow for long exposures providing very deep photometry of point sources, reaching a S/N of 10 for a $V = 26$ B5V star in a 45 minute exposure.

Two cameras, named $f/48$ and $f/96$ after their original focal ratios, are available on the FOC, but difficulties with the $f/48$ camera have made the $f/96$ camera the FOC's workhorse, responsible for virtually all of the imaging. Since the installation of COSTAR, the $f/48$ camera has been used exclusively for long-slit spectroscopy. Observers should be aware that the names of these cameras no longer describe their actual focal ratios. COSTAR has raised the f /ratio of HST's Optical Telescope Assembly (OTA) from $f/24$ to $f/37$, increasing the f /number of the two FOC cameras from $f/48$ to $f/75.5$ and from $f/96$ to $f/151$. However, because

the original names are deeply rooted in the HST ground system at all levels, from proposal entry to data archiving, we have been forced to retain these names. Table 4.1 summarizes the post-COSTAR imaging characteristics of the FOC.

Table 4.1: Summary of FOC Performance Characteristics

Optical Modes	f/48 ^a	f/96
Focal ratio	75.5	151
Operating range (Å)	1150–6500	1150–6500
Number of bandpass filters	11	39
Bandpass FWHM (Å) max	2700	2300
Bandpass FWHM (Å) min	300	34
Maximum ND attenuation (mag.)	0	9
Field of view (arcsec) max	28 x 28	14 x 14
Field of view (arcsec) min (128x128)	3.6 x 3.6	1.8 x 1.8
Unzoomed pixel size (arcsec)	0.029	0.014
Minimum wavelength for critical sampling (Å)	6500	3250
Peak efficiency (%)	6.6	7.9
Peak wavelength (Å)	3400	3700
Limiting magnitude, point source ^b	27	27.5
Limiting magnitude arcsec ⁻² , extended source ^c	23.5	23
Dynamic range, point source ^d (mag)	20–27	19–27.5
Dynamic range, extended source ^e (mag arcsec ⁻²)	18–25	17–25
Overload magnitude	9	9
Number of polarizing prisms ^f	0	3

a. The f/48 mode has been available for long slit spectroscopy in Cycles 6 and 7.

b. S/N = 5, 5 hour integration, U band.

c. Same as b. over 0.1" x 0.1" area.

d. 2 counts sec⁻¹ pixel⁻¹ upper limit.

e. 0.5 counts sec⁻¹ pixel⁻¹ upper limit.

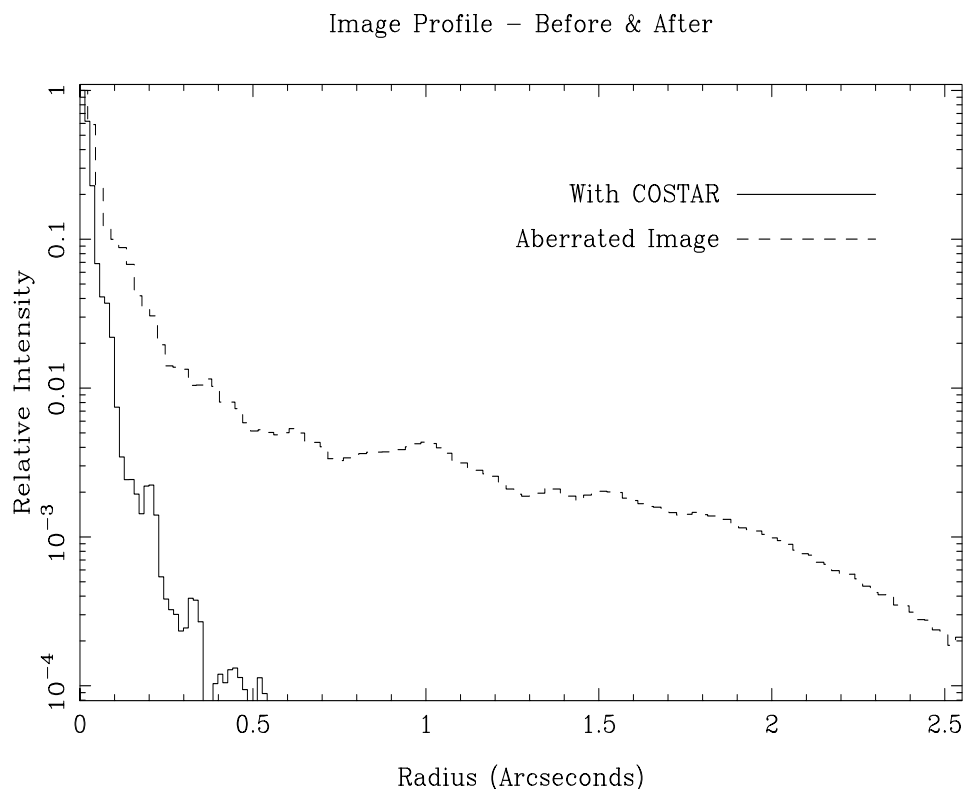
f. 0 degrees, 60 degrees, 120 degrees direction of polarization.

4.1 Spatial Resolution and PSF

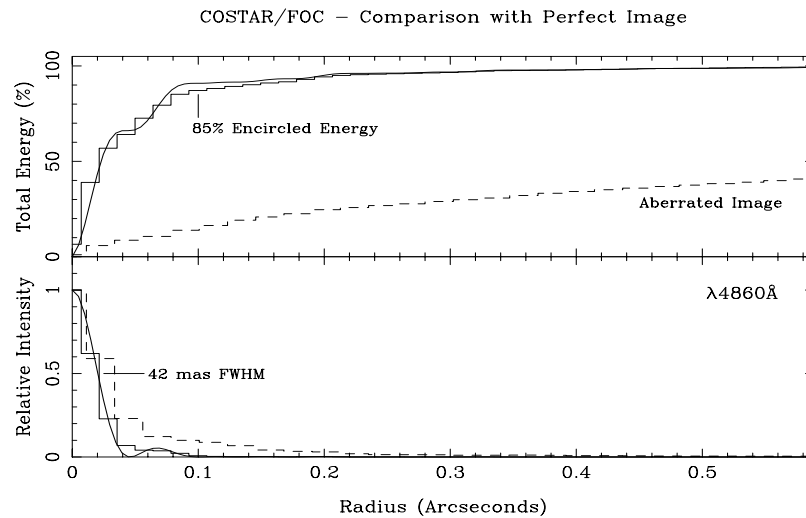
COSTAR has restored many of the FOC's envisioned capabilities, in that the COSTAR-corrected PSF contains more than 75% of the visible light within a radius of 0.1 arcsecond, while losing less than 20% of the light to the two reflections at the two extra mirror surfaces. The net increase in sensitivity is a

factor of approximately 3-4 at visible wavelengths. COSTAR's improvement of the FOC PSF is illustrated in Figure 4.1, which shows the radial profile of an aberrated PSF image and a COSTAR-corrected image at 4860Å. Archive users should consult the *FOC Instrument Handbook*, version 3.0 for more details on the pre-COSTAR characteristics of the FOC.

Figure 4.1: PSF Before and After COSTAR



The encircled energy fraction $\mathcal{E}(\lambda)$ is tabulated in the *FOC Instrument Handbook*, version 7.0 (Table 9) for various circular apertures. This quantity is normalized so that the encircled energy is 1.0 at a radius of 1 arcsecond (70 pixels). Figure 4.2 compares the encircled energy curves of the aberrated OTA, the COSTAR-corrected OTA, and a perfect diffraction-limited image from a 2.4m circular aperture with a 0.33 central obstruction, showing that the COSTAR-corrected FOC PSF approaches that of an ideal imaging system in both encircled energy performance and in the FWHM of the PSF core.

Figure 4.2: Encircled Energy Fraction and PSF Profile Before and After COSTAR

4.2 Filters

The FOC has six commandable rotating filter wheels holding 58 optical elements and six clear apertures. Four wheels are on the $f/96$ camera, and two are on the $f/48$ camera. The filter wheels of the $f/96$ camera have long pass, wide band, medium band, narrow band and neutral density filters. They also contain three polarizers and two objective prisms. The filter wheels of the $f/48$ camera contain long pass, wide band, and three objective prisms. Tables 3 and 4 of the *FOC Instrument Handbook*, version 7.0, gives a complete list of the optical elements ordered by increasing peak wavelengths and provides information on their transmission and wavelength coverage. This table also lists the magnitudes of attenuation of the neutral density filters, which can diminish the beam in increments of one magnitude from one to nine magnitudes.

4.3 Formats & Fields of View

The FOC $f/96$ camera has a maximum field of view of 14 x 14 arcseconds square, obtained with the 512 x 1024 zoomed format, although the dynamic range of this format is limited. The FOC can operate with normal pixels (square, 25 x 25 microns) or zoomed pixels (rectangular, 50 x 25 microns). Normal pixels provide a plate scale of 0.01435 arcsec pixel⁻¹ for the $f/96$ camera, and 0.02870 arcsec pixel⁻¹ for the $f/48$ camera. Zoomed pixels are twice as long in the x direction. All formats larger than 512 x 512 pixels automatically have an 8-bit word length. Table 4.2 and Table 4.3 provide the main characteristics of the standard formats for the $f/96$ and $f/48$ camera respectively, where the first column gives the format size (S x L), the second the pixel size in microns, the third the starting point in

pixels, the fourth the word length, the fifth the zoom configuration, and the sixth the overall field of view in arcseconds squared for that format.

Table 4.2: Available f/96 Formats

Format (S x L)	Pixel Size (μm^2) (arcsec ²)	Offset (S ₀ ,L ₀)	Word Length	Zoom	FOV (arcsec ²)
512 x 1024	50 x 25 (0.029 x 0.014)	0,0	8 bit	on	14 x 14
512 x 1024	25 x 25 (0.014 x 0.014)	256,0	“ “	off	7 x 14
512 x 512	50 x 25 (0.029 x 0.014)	0,256	16 bit	on	14 x 7
512 x 512	25 x 25 (0.014 x 0.014)	256,256	“ “	off	7 x 7
256 x 256	“ “	384,384	“ “	“ “	3.6 x 3.6
128 x 128	“ “	448,448	“ “	“ “	1.8 x 1.8

Table 4.3: Available f/48 Formats

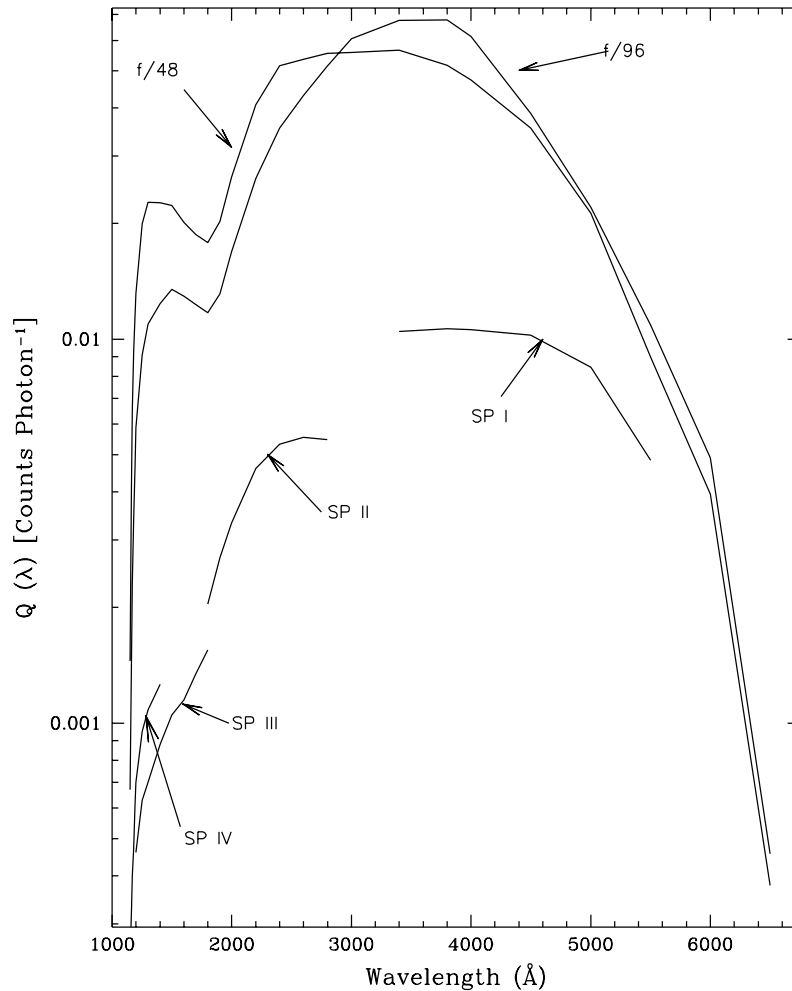
Format (S x L)	Pixel Size (μm^2)	Offset (S ₀ ,L ₀)	Word Length	Zoom	FOV
512 x 1024 (imaging)	50 x 25 (0.057" x 0.029")	0,0	8 bit	on	28" x 28"
512 x 1024 (spec)	50 x 25 (0.057" x 1.7Å)	0,0	8 bit	on	28" x 1700Å
512 x 1024 (spec)	25 x 25 (0.029" x 1.7Å)	192,0	8 bit	off	14" x 1700Å
256 x 1024 (spec)	25 x 25 (0.029" x 1.7Å)	320,0	16 bit	off	7" x 1700Å

4.4 Sensitivity

The overall (OTA + COSTAR + FOC) central absolute quantum efficiency in counts photon⁻¹ with no filters in the beam is plotted and tabulated as a function of wavelength in Figure 4.3 (and also Table 11 of the *FOC Instrument Handbook*, version 7.0), for the four FOC imaging and spectrographic configurations. The data represent the product of in-orbit measurements for the f/96 relay+OTA absolute quantum efficiency, and ground-based reflectance calibrations of the COSTAR mirrors for the f/48. The predicted loss of light from two reflections of MgF₂ coated aluminum COSTAR mirrors amounts to a 20% loss in the visible and a 35% loss in the ultraviolet. The loss due to the COSTAR mirrors is more than compensated by the improvement in image quality, because the encircled

energy performance within a 0.1" radius has improved from 18% to $\cong 80\%$ within the same area.

Figure 4.3: Baseline Overall Quantum Efficiency.



4.5 Polarization & Spectroscopy

In addition to standard imaging, the FOC can also perform polarization imaging, objective prism spectroscopy, and long-slit spectroscopy.

- Three polarizer filters available on the $f/96$ camera, with pass directions of 0 degrees, 60 degrees and 120 degrees, provide a straight-through, low reflection-angle system which introduces less than 2% intrinsic polarization.
- Two objective prism filters on the $f/96$ camera allow observers to obtain high-throughput spectra at low to medium resolution from 1700Å to 6000Å (near-UV prism) and 1150Å to 6000Å (far-UV prism).

- The $f/48$ camera possesses a long-slit spectroscopy facility with a resolving power of ~ 1150 in 4 orders, covering 3600–5400 Å, 1800–2700 Å, 1200–1800Å, and 1150–1350 Å.

4.6 What to Expect

This section highlights some typical FOC image characteristics. Rather than trying to present examples of every possible mode, we focus on the $f/96$ imaging mode, because it is the most commonly used. Examples of $f/48$ images, $f/48$ longslit spectra, and prism images appear in later sections.

Keep in mind that the grayscale representations used in this manual seldom highlight the subtleties of the data. There is no substitute for actually displaying the data on a monitor.

Some images in this section are displayed with higher intensities as white and lower intensities as black (positive), other images are displayed the opposite way (negative).

Commonly Observed Features

If your FOC data are well-exposed, you might see one or more of the following:

- Occulting fingers located near the aperture entrance if the image size is greater than 512 x 512 pixels or if the FUV prism is in the beam.
- Reseau marks etched onto the faceplate of the detector to aid in geometric correction (Figure 4.4).
- Blemishes (scratches on the faceplate, Figure 4.4).
- Vertical intensity variations along the right edge of the image (due to a variation in camera scan speed).
- A faint diagonal parallel striping pattern called *pattern noise*.

After geometric correction your images may additionally show:

- A very faint moiré pattern (“thumbprint”), which is a variation of the noise, *not the signal*, caused by the geometric correction (Figure 4.5).
- Warped edges (Figure 4.4).

These features are all normal and should be expected. They can be traced either to the instrumental design and performance of the FOC or the calibration process which corrects for geometric distortion.

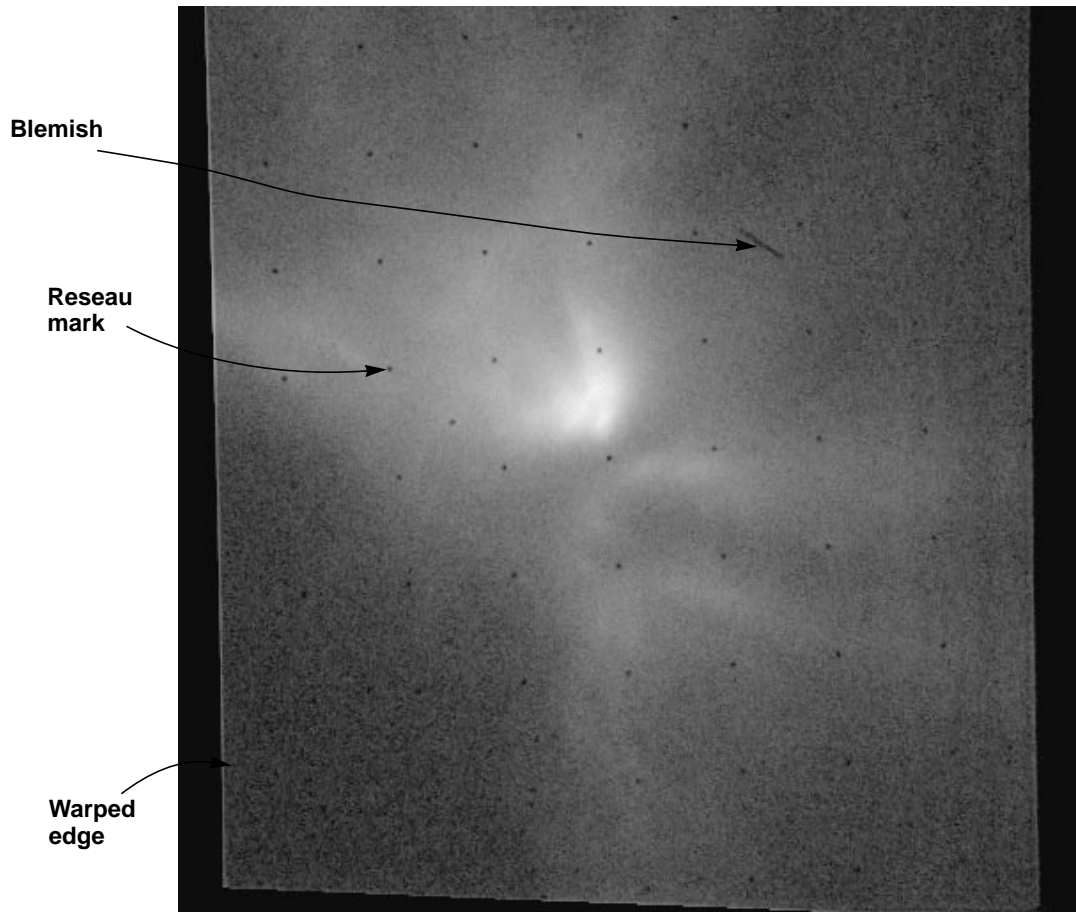
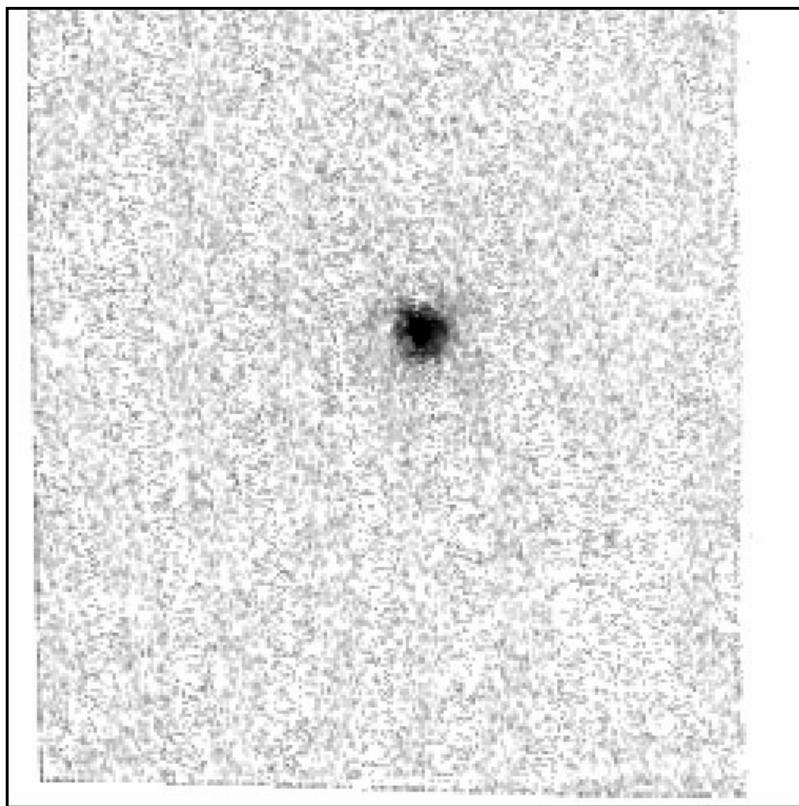
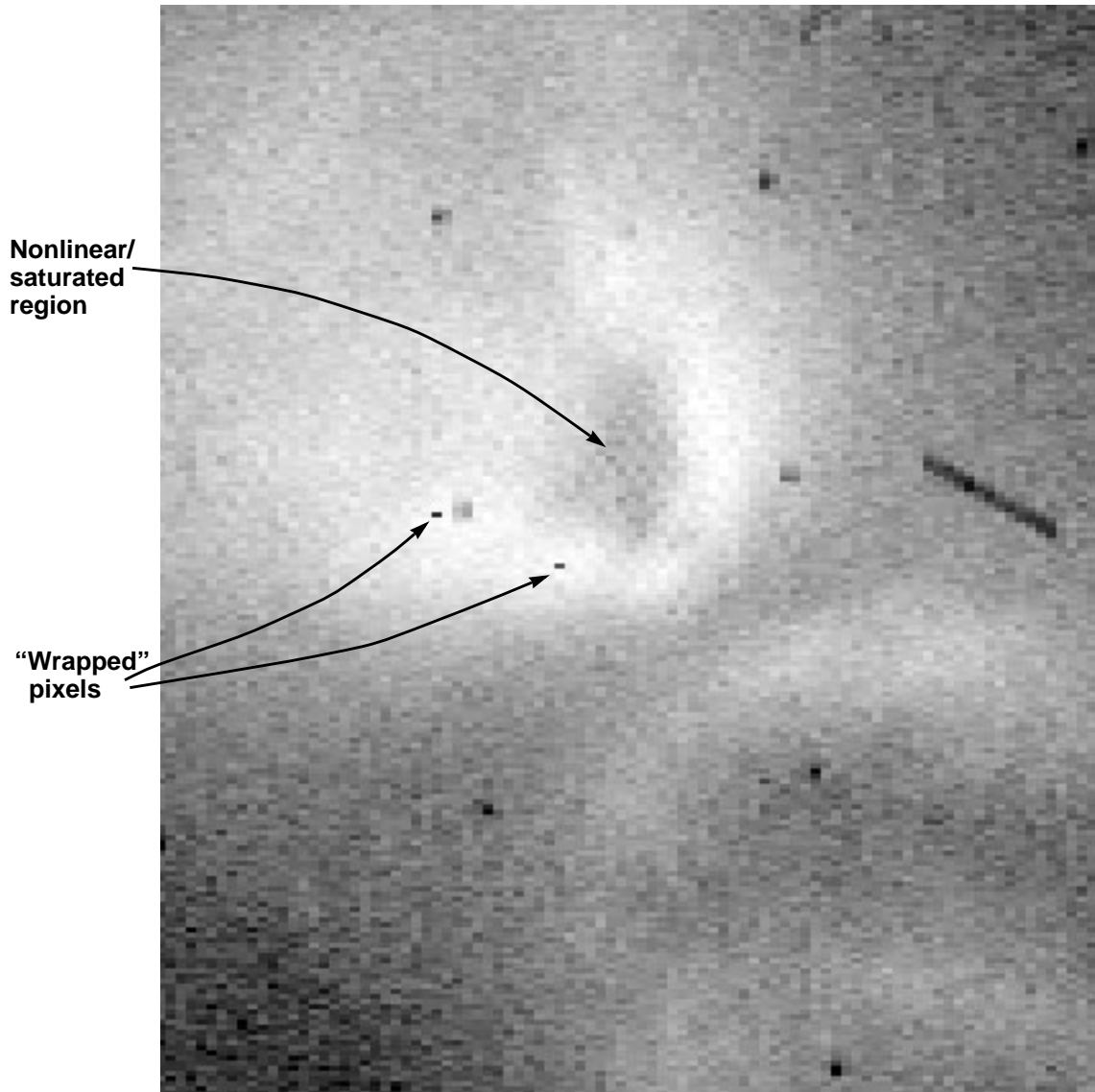
Figure 4.4: FOC $f/96$ Image of an Extended Source

Figure 4.4 is a positive rendition of an $f/96$ (F430W) 512 x 512 image of the reflection nebula LK-H alpha 233. The image has been fully calibrated by the FOC pipeline and shows features that are common in any well-exposed FOC image. The regular grid of reseau spots are used for geometric distortion calibration. The warped edges are produced by the pipeline during the geometric transformation. A blemish is seen above and to the right of center.

Figure 4.5: FOC 512x512 Image Showing Faint “Thumbprint” Pattern or “Fringes”

Images that have been geometrically corrected often show the pattern evident in the above grayscale picture: a thumbprint pattern at low intensity levels. It is quite hard to see, appearing most clearly when the image has a low (~ 1 count per pixel or so) spatially flat background. The thumbprint pattern is a modulation of the local noise characteristics of the data, not of the intensities themselves. It is a by-product of the geometric correction process in which the raw (geometrically distorted) image is resampled with an interpolator that takes a weighted mean of the four nearest pixels to determine the geometrically corrected pixel value (see “Geometric Correction (GEOCORR)” on page 6-5 for details). The weightings vary smoothly with position in the image, such that at some places, a single pixel dominates the weightings (the noise of the resampled pixel is the same as that of the original data), while at other places the weightings favor all four pixels equally (the average noise is half of the noise of the individual pixels). The fringes are contours of constant weighting.

The actual pattern depends on the particular geometric correction file used, and thus depends on the format. The effect on the scientific utility of the data is minimal, unless one requires accurate values of the noise per pixel for each pixel.

Figure 4.6: Full-Format $f/96$ Image of a Bright Extended Source

The portion of a full-format $f/96$ image shown above illustrates 8-bit wrapover and saturation. The former occurs when the image format selected is 512×1024 (zoomed or unzoomed). In that case, the image memory is configured so that there are only 8 bits per pixel. The maximum pixel intensity in raw full-format data is therefore only 255 counts; a further detected photon in a pixel causes the recorded intensity to cycle back to zero. After dezooming a full-format image, the maximum pixel intensity in the raw data is $255/2 = 127.5$. The two pixels indicated have suffered from wrapover—they appear as rectangular because the raw dezoomed image is displayed. The dark region is an area where the photon count rate is higher than the FOC can count without suffering coincidence losses.