**PART 3:**

# Faint Object Spectrograph

This part introduces the basics of the Faint Object Spectrograph (FOS) and gives guidelines for reducing FOS spectra. It is intended as a general tool for helping users to work with FOS data taken at any time, be it pre-COSTAR or post-COSTAR. This approach differs from that of the *FOS Instrument Handbook*, which gives up-to-date information on the instrument performance for use in submitting HST observing proposals. The current version of the Instrument Handbook (version 6.0) will be the last if the FOS is taken out of the telescope, as planned, during the next servicing mission in February of 1997.

This part provides general information, including hints and pointers telling you how to get more detailed information about handling data in each special case. Several data reduction steps will be explained, showing before- and after-processing examples of data exhibiting certain characteristics.

The FOS information spans several chapters: first, we will introduce the instrument and the different modes in which it takes data. Then we will describe how to compare a planned observation with the dataset returned from an executed observation to determine how the real data compares to what you expected. This will be followed by a description of how data are calibrated in the Routine Science Data Processing (RSDP) pipeline, problems that can arise in this procedure, and how—if necessary—you can recalibrate your data with updated calibration files. We also describe some calibration problems specific to FOS data and discuss some of its specific instrument characteristics.

HST data quality is not a fixed property! Calibration data are taken and evaluated continuously, allowing improved calibration of new data, previously delivered data, and data from the archive. This document can help you realize the highest possible data quality, even if your data show no obvious signs of calibration error.

# More Information on FOS

Additional information about the Faint Object Spectrograph can be requested through the Help Desk via e-mail to: `help@stsci.edu`. The listing of all available documents is available through STEIS using the following URL:

`http://www.stsci.edu/ftp/instrument_news/FOS/fos_bib.html`

# CHAPTER 12: FOS Instrument Overview

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This chapter provides the most basic information needed to understand the geometry of the FOS instrument and the optical components affecting the light path. Quantitative descriptions of the instrument performance and capabilities are found in the *FOS Instrument Handbook*.

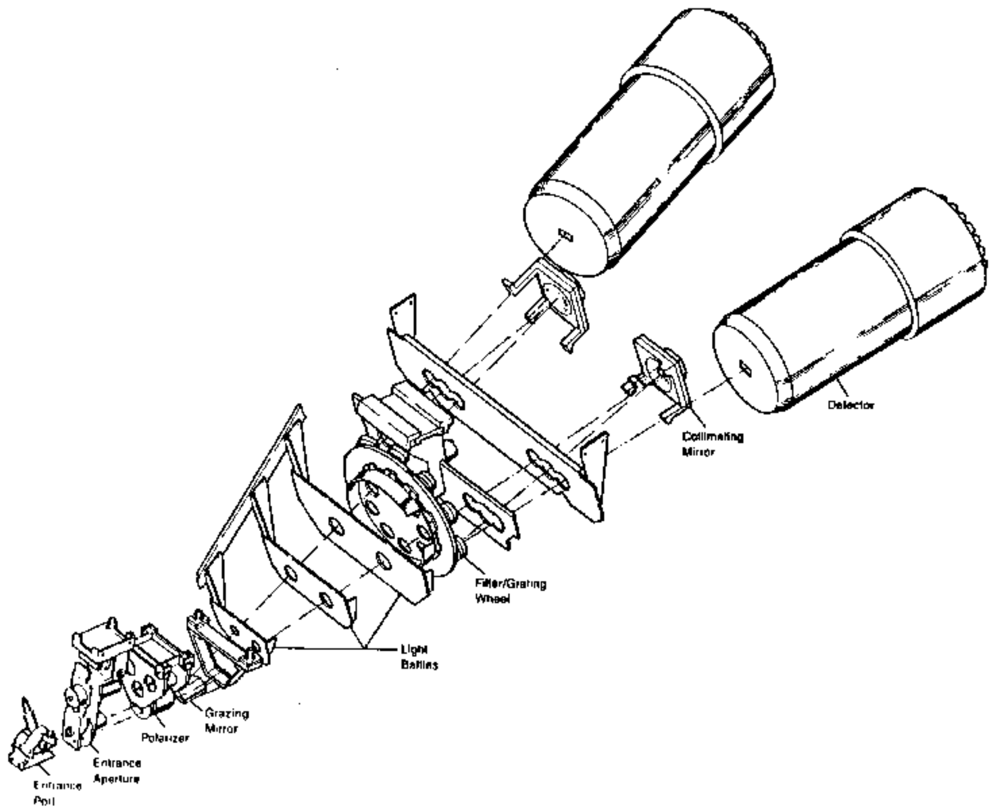
## Instrument Basics

The FOS has two Digicon detectors with independent optical paths (Figure 12.1). The Digicons operate by accelerating photoelectrons emitted by a transmissive photocathode onto a linear array of 512 diodes. The blue detector (FOS/BL) is sensitive from 1150 Å to 5400 Å, while the red Digicon (FOS/RD) covers the wavelength range from 1620 Å to 8500 Å. Figure 12.2 shows the quantum efficiencies of both detectors. Note that the graphs in Figure 12.2 are provided for illustration only; the plotted values are not accurate enough for quantitative use in data analysis. The general characteristics of FOS/BL and FOS/RD are compiled in Table 12.1. Details, such as the spectral resolution as a function of aperture size and source extent, can be found in the *FOS Instrument Handbook*.

The FOS has several apertures for different scientific purposes. There is a large aperture for acquiring targets using on-board software (3".7 x 3".7; designation 4.3[1]). Since the diode array extends only 1".3 in the direction perpendicular to the

1. The aperture sizes are post-COSTAR values, while the designations are pre-COSTAR, and are therefore somewhat inconsistent.

**Figure 12.1:** FOS Optical Path




dispersion, this largest aperture has an effective collecting area of 3″.7 x 1″.3. Other apertures include several circular apertures with sizes 0″.86 (1.0), 0″.43 (0.5), and 0″.26 (0.3), as well as paired square apertures with sizes 0″.86 (1.0-PAIR), 0″.43 (0.5-PAIR), 0″.21 (0.25-PAIR), and 0″.09 (0.1-PAIR), for isolating spatially resolved features and for measuring the sky. In addition, a slit and two barred apertures are available (Figure 12.1 and Table 12.2).

**Figure 12.2:** Detector Quantum Efficiencies

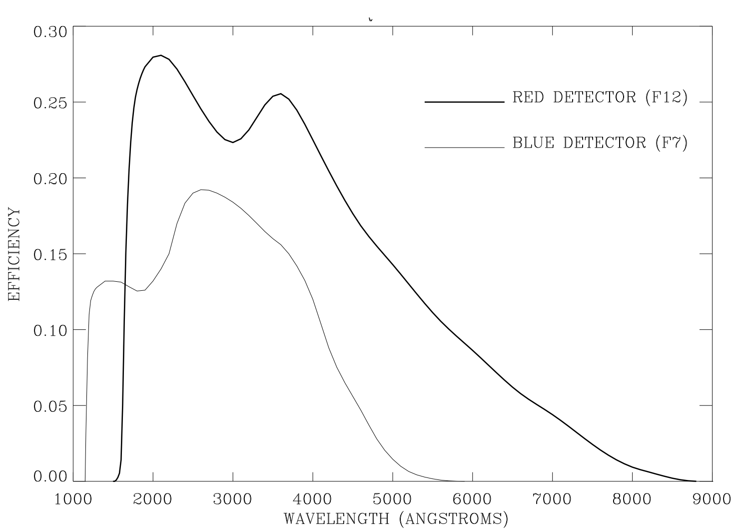


**Table 12.1:** Detector Characteristics

| Attribute | Value |
|---|---|
| Wavelength coverage | FOS/BL: 1150Å to 5400Å in several grating settings.<br>FOS/RD: 1620Å to 8500Å in several grating settings. |
| Spectral resolution | High: $\lambda/\Delta\lambda \approx 1300$.<br>Low: $\lambda/\Delta\lambda \approx 250$. |
| Time resolution | $\Delta t \geq 0.033$ seconds. |
| Acquisition aperture | 3.7″ x 3.7″ (4.3). |
| Science apertures | Largest: 3.7″ x 1.3″ (4.3).<br>Smallest: 0.09″ square paired (0.1-PAIR). |
| Brightest stars observable | V≈ 9 for B0V, V≈7 for G2V, depending on spectral type and wavelength |
| Dark count rate | FOS/BL: 0.0064 counts $s^{-1}$ $diode^{-1}$<br>FOS/RD: 0.0109 counts $s^{-1}$ $diode^{-1}$ |
| Example exposure times<br>0.9″ (1.0) aperture | $F_{1300}$=2.5 x $10^{-13}$, SNR=20/(1.0Å), t=260s.<br>$F_{2800}$=1.3 x $10^{-13}$, SNR=20/(2.0Å), t=10s (FOS/BL).<br>$F_{2800}$=1.3 x $10^{-13}$, SNR=20/(2.0Å), t=6.6s (FOS/RD). |

A variety of dispersers is available on the FOS; their designations and basic properties are collected in Table 12.3. Each disperser directs incoming light onto a different location on the photocathode. From the photocathode, electrons are deflected magnetically without magnification onto the diode array of the Digicon. In this way the light transmitted by the aperture is projected onto the diode array. The relative size of the different apertures as they are projected onto a section of the diode array is displayed in Figure 12.3. The individual diodes are spaced 0″.31 (post-COSTAR) or 0″.36 (pre-COSTAR) along the dispersion direction and are 1″.29 (1″.43) tall perpendicular to it. In this handbook, we refer to the dispersion direction as the *x-direction*, the y-axis of the FOS is perpendicular to the dispersion and we call this the *y-direction*. The deflection of the photoelectrons is controlled by an internal magnetic field, which in turn depends on a high-voltage setting. The unit of distance in the y-direction is the so-called *y-base unit*. The high voltage is adjusted so that 256 y-base units correspond to the height of the diodes (pre and post-COSTAR).

**Table 12.2:** FOS Apertures

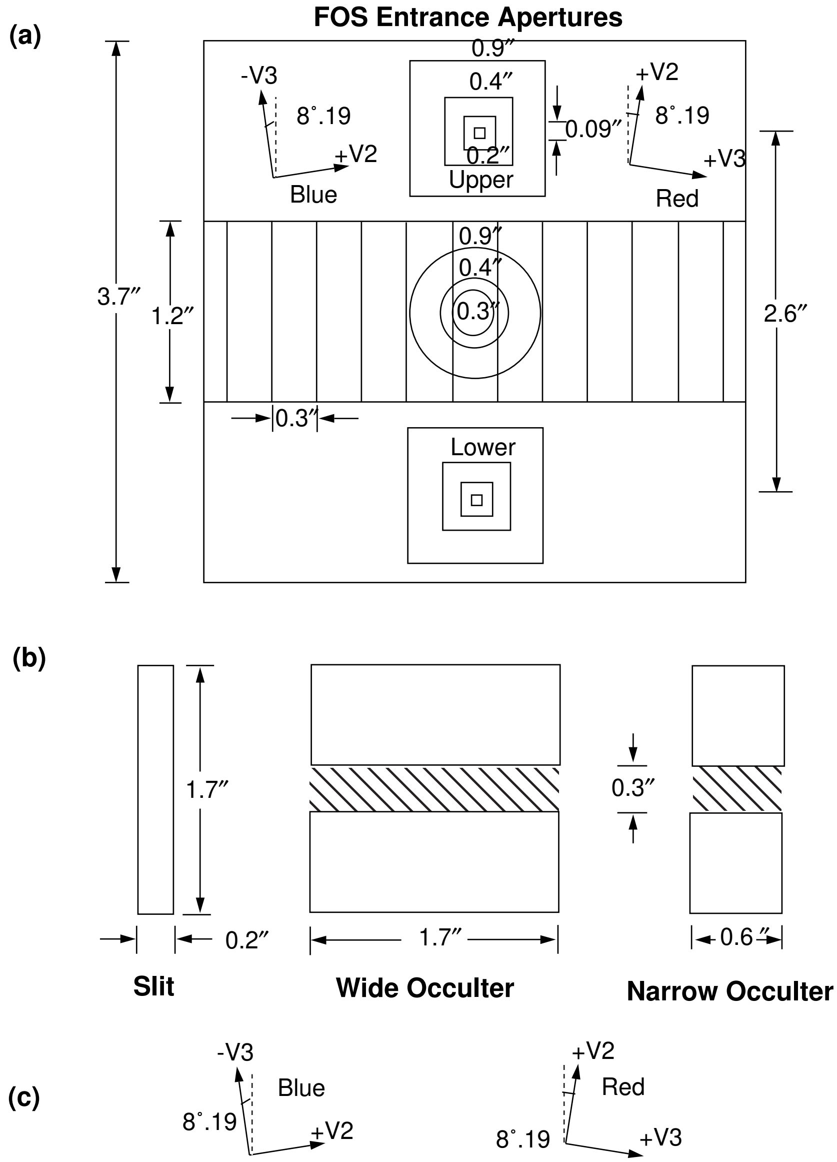
| Designation (Header Designation) | Number | Shape | Size (″) | Separation (″) |
|---|---|---|---|---|
| 0.3 (B-2) | Single | Round | 0.26 dia | NA |
| 0.5 (B-1) | Single | Round | 0.43 dia | NA |
| 1.0 (B-3) | Single | Round | 0.86 dia | NA |
| 0.1-PAIR (A-4) | Pair | Square | 0.09 | 2.57 |
| 0.25-PAIR (A-3) | Pair | Square | 0.21 | 2.57 |
| 0.5-PAIR (A-2) | Pair | Square | 0.43 | 2.57 |
| 1.0-PAIR (C-1) | Pair | Square | 0.86 | 2.57 |
| 0.25X2.0 (C-2) | Single | Rectangular | 0.21 x 1.71 | NA |
| 0.7X2.0-BAR (C-4) | Single | Rectangular | 0.60 x 1.71 | NA |
| 2.0-BAR (C-3) | Single | Square | 1.71 | NA |
| BLANK (B-4) | NA | NA | NA | NA |
| 4.3 (A-1) | Single | Square | 3.66 x 3.71 | NA |
| FAILSAFE | Pair | Square | 0.43 and 3.7 | NA |

**Table 12.3:** Dispersers Available on FOS

| Grating | Diode No. at Low λ | Low λ (Å) | Diode No. at High λ | High λ (Å) | Δλ (Å-Diode$^{-1}$) | Blocking Filter |
|---|---|---|---|---|---|---|
| **Blue Digicon** | | | | | | |
| G130H | 53 | 1140[a] | 516[b] | 1606 | 1.00 | -- |
| G190H | 1 | 1573 | 516 | 2330[c] | 1.47 | -- |
| G270H | 1 | 2221 | 516 | 3301 | 2.09 | $SiO_2$ |
| G400H | 1 | 3240 | 516 | 4822 | 3.07 | WG 305 |
| G570H | 1 | 4574 | 516 | 6872[d] | 4.45 | WG 375 |
| G160L | 319 | 1140[a] | 516 | 2508[c] | 6.87 | -- |
| G650L | 295 | 3540 | 373 | 9022[d] | 25.11 | WG 375 |
| PRISM[e] | 333 | 1500[f] | 29 | 6000[d] | -- | -- |
| **Red Digicon[i]** | | | | | | |
| G190H | 503 | 1590[g] | 1 | 2312 | -1.45 | -- |
| G270H | 516 | 2222 | 1 | 3277 | -2.05 | $SiO_2$ |
| G400H | 516 | 3235 | 1 | 4781 | -3.00 | WG 305 |
| G570H | 516 | 4569 | 1 | 6818 | -4.37 | WG 375 |
| G780H | 516 | 6270 | 126 | 8500[h] | -5.72 | OG 530 |
| G160L | 124 | 1571[g] | 1 | 2424 | -6.64 | -- |
| G650L | 211 | 3540 | 67 | 7075 | -25.44 | WG 375 |
| PRISM[e] | 237 | 1850 | 497 | 8950[h] | -- | -- |

a. The blue Digicon $MgF_2$ faceplate absorbs light shortward of 1140 Å.
b. The photocathode electron image typically is deflected across 5 diodes, effectively adding 4 diodes to the length of the diode array.
c. The second order overlaps the first order longward of 2300 Å, but its contribution is at a few percent.
d. Quantum efficiency of the blue tube is very low longward of 5500 Å.
e. PRISM wavelength direction is reversed with respect to gratings of the same detector.
f. The sapphire prism absorbs some light shortward of 1650 Å.
g. The red Digicon fused silica faceplate strongly absorbs light shortward of 1650Å.
h. Quantum efficiency of the red detector is very low longward of 8500 Å.
i. Dispersion direction is reversed for `FOS/RD` relative to `FOS/BL`.

**Figure 12.3:** Aperture Sizes Projected On Diode Array




In order to minimize external influences on the magnetic deflection of electrons from the photocathode onto the diode array, both Digicons are magnetically shielded. However—especially on the red side—the shielding is inadequate. Thus, the telescope's orientation relative to the earth's magnetic field influences the characteristics of the FOS. This is the so-called *geomagnetically induced image motion* (GIM) problem. In order to minimize this effect, on-board software was developed to compensate for this error. A residual uncertainty remains, however, which affects the calibration accuracy of the instrument, as described further on page 238.

# Observing Modes

## Target Acquisition

Before observing a target, it must, naturally, be located in the instrument aperture. Several techniques for target acquisition have been developed and will be described in this chapter. Only after the target is acquired can the science exposure be started. We will describe science data acquisition in the next section.

Note: Starting approximately November 1, 1992 (in Cycle 2) FOS calibration measurements are conducted with the highest possible pointing accuracy, i.e., with the target as close as possible (≤ 0.04) to the center of the aperture. Thus, the FOS instrument performance is best understood for the very center of the apertures. The accuracy inherent to your choice of target acquisition mode will therefore determine the calibration accuracy that can later be reached, i.e., how closely STScI's calibrations apply to your observations.

FOS data can be obtained through several different apertures, ranging from 0".09 to 3".7 in size for post-COSTAR data (0".1 to 4".3 pre-COSTAR). The target is centered in the chosen aperture using one of four methods:

- Blind pointing.
- One of the FOS target acquisition techniques listed below.
- Via an interactive or WFPC2-assisted acquisition.
- Via a GHRS-assisted acquisition.

The FOS target acquisition modes and their corresponding header keyword values found in the standard header packets (`.shh` file) are:

- ***Binary acquisition***: (keyword value OPMODE=ACQ/BINARY).
- ***Interactive***: (keyword value OPMODE=ACQ).
- ***Peak-up or peak-down***: (keyword value OPMODE=ACQ/PEAK).
- ***Firmware***: (keyword value OPMODE=ACQ/FIRMWARE).

In order to avoid unnecessary overhead times, a new technique has been developed for proposals that require more than one visit to a target within a few days (up to two months). This *reuse target offsets* method allows the instrument to use a target offset that was derived in the acquisition for the first visit during subsequent visits so that these later visits need only a single-stage peak-up/peak-down acquisition to reconfirm the correct centering of the target in the aperture.

A much more detailed description of all different target acquisition modes is given in the *FOS Instrument Handbook*.

Target acquisition observations produce science datasets. Thus, for each set of FOS observations of a given source the dataset taken first will be the FOS target acquisition image.[2] This image will be easily identifiable, because the header keyword GRNDMODE will be set to ACQ, and the header keyword OPMODE (in the `.shh` file) will be set to the requested target acquisition mode. With the FOS, it is also possible to take an *image* of the photocathode with the mirror in place following the target acquisition; such an image observation will have a keyword value of OPMODE=IMAGE. The target acquisition data can later be used to determine how well the source was centered in the aperture.

Note: Although target acquisition data are not substepped and overscanned, they may still contain scientifically valuable information and are thus delivered to the observer on tape.

## Science Data Acquisition

To maximize the science data output from the FOS, you would normally oversample spectra and shift the object spectrum with respect to the diode array during several subintegrations. These two procedures are called *substepping* and *overscanning*.

Substepping is used to better sample the spectrum in the wavelength direction and overscanning is used to assure that each pixel in the final spectrum contains data received from multiple diodes (to smooth out diode-to-diode variations and insure against data loss when a single diode is disabled). Both substepping and overscanning rely on the magnetic focus assembly in the Digicon detector to magnetically deflect the photoelectrons in the dispersion direction so that they fall on slightly different locations on the diode array.

For substepping, the spectrum is deflected by a fraction of a diode in the dispersion direction (where the fraction is given by 1/NXSTEPS and NXSTEPS is a header keyword). The diodes are read out into unique memory locations for each substep and the substepping is performed NXSTEPS times.

For overscanning, the process of substepping is continued over more than one diode in the dispersion direction. A complete round of substepping is performed for each overscan step. The number of overscan steps performed is determined by the overscan parameter (header keyword OVERSCAN). Each time a given wavelength position is deflected onto and measured by a new overscan diode, its counts are co-added into the same memory location in the FOS microprocessor. When using the full diode array, the result is a spectrum with 512 * NXSTEPS plus a small number (NXSTEPS x (OVERSCAN – 1)) of *edge* pixels. Each pixel (excluding the edge pixels) has data contributed from the number of diodes specified by OVERSCAN. Thus, substepping changes the number of pixels in the final spectrum; and overscanning principally changes the number of diodes that

2. If a blind pointing is done, there will obviously be no target acquisition image produced, unless one was specifically requested.

contribute to a single pixel. Although the number of diodes in the diode array is only 512, the number of pixels in an ACCUM mode observation is given by the equation:

$$\textit{\# of pixels} = (\textit{\# of diodes} + (\text{OVERSCAN} - 1)) \times \text{NXSTEPS}$$

The default values of NXSTEPS=4 and OVERSCAN=5 yield a typical ACCUM mode spectrum of 2064 pixels. A given diode will have contributed to the data in (NXSTEPS x OVERSCAN) pixels.

The mode in which a given dataset is taken is identified in the data headers by the keywords OPMODE and GRNDMODE. The OPMODE (`.shh`) and GRNDMODE (`.d0h`, `.c1h`) keyword values are listed at the beginning of each of the following sections describing the individual modes and are also identified in the following list of available modes:

- ***Spectrophotometry***: OPMODE=ACCUM, GRNDMODE=SPECTROSCOPY
- ***Time-resolved spectrophotometry***: OPMODE=PERIOD, GRNDMODE=TIME RESOLVED
- ***Rapid readout***: OPMODE=RAPID, GRNDMODE=RAPID READOUT
- ***Spectropolarimetry***: OPMODE=ACCUM, GRNDMODE=SPECTROPOLARIMETRY

## Spectrophotometry Mode

Spectrophotometry mode is identified by an OPMODE keyword value of "ACCUM" and a GRNDMODE keyword value of "SPECTROSCOPY". For the standard ACCUM mode, the default value of NXSTEPS is 4 and OVERSCAN is 5 (see above).

ACCUM mode spectra with a total exposure time lasting more than a few minutes are read out at regular intervals to the ground or to the onboard tape recorders. The frequent readouts protect against catastrophic data loss. Since the data are read out at regular intervals, all observations longer than a few minutes (the time between readouts is usually about two minutes for the red detector and usually about four minutes for the blue detector) are time resolved. Each readout is stored in the data files as follows: The first readout is stored as group one, the next readout is added (accumulated) to the previous readout and the sum is stored as group two, and so on. The last group contains the spectrum from the full exposure time of the observation. The number of groups per observation depends on the length of the exposure and the detector used. More information on the different data files from ACCUM observations is available in "Contents of Data Tapes" on page 211 and "Details of the FOS Pipeline Process" on page 235.

Raw paired aperture data are stored as concatenated data per group, i.e., data from apertures A and B are stored together in one group in the raw data files, similar to spectropolarimetry data for each pass direction (instead of only one spectrum per group, as for the single apertures).

## Time-Resolved Spectrophotometry Mode

Time-resolved spectrophotometry mode is identified by the keyword values OPMODE=PERIOD and GRNDMODE=TIME RESOLVED. This mode is normally used for objects with known periodicity in the 50 msec to 100 sec range. To maintain the phase information of these observations, the known period (CYCLE-TIME) of the object is divided into *bins* or *slices*, where each bin has a duration time = period/BINS. The spectra acquired in this mode are stored in the different bins which correspond to a given phase of the period. The information obtained in each period is added correctly to the pattern so that the phase information is maintained (so long as the period is known accurately).

Note that relativistic aberration is important for short periods and long observations). However, there is no correction for light travel time across the orbit.

The raw (`.d0h`) data file for time-resolved mode contains a single data group that is made up of all the individual spectral slices (or bins) stored sequentially. For example, if an observation used 374 detector channels, with NXSTEPS=1, OVERSCAN=5, and SLICES=32, the `.d0h` file would contain one data group having a total length of:

$$(374 + (5 - 1)) \times 1 \times 32 = 12096 \text{ pixels}$$

The calibrated flux, wavelength, error, and data quality files will have the data from the individual slices (bins) broken out into separate groups. For the example above, the `.c0h`, `.c1h`, `.c2h`, and `.cqh` files would have 32 groups of 378 pixels.

The `.c3h` file is organized as follows. Groups 1 and 2 contain the average flux and average errors, respectively, of all the individual calibrated spectra. Following these, there are pairs of groups where the first group in each pair contains the difference between an individual flux spectrum and the average, and the second group in each pair contains the sum of the errors for the individual spectrum and the average. See “Details of the FOS Pipeline Process” on page 235 for details on how the average and difference spectra are generated. For example, if the observation consisted of 32 slices, the structure of the `.c3h` file would be that shown in Table 12.4.

**Table 12.4:** Group Structure of .c3h File with 32 Slices

| Group # | Contents |
|---|---|
| 1 | Average of all 32 flux spectra from the .c1h file |
| 2 | Average of all 32 error spectra from the .c2h file |
| 3 | Spectrum 1 minus average |
| 4 | Combined spectrum 1 and average errors |
| 5 | Spectrum 2 minus average |
| 6 | Combined spectrum 2 and average errors |
| ... | ... |
| 65 | Spectrum 32 minus average |
| 66 | Combined spectrum 32 and average errors |

## Rapid Readout Mode

Rapid readout mode is identified by the keyword values OPMODE=RAPID and GRNDMODE=RAPID READOUT. For certain astronomical targets where rapid variability in flux is suspected, but the precise period is unknown, or the expected variation is aperiodic, the PERIOD mode of data acquisition is unsuitable because the bin folding period must be specified. In such cases the RAPID readout mode is used. In this mode, the data are acquired using the normal substepping and overscanning techniques. The spectra are read out at intervals (chosen by the observer according to the scientific goals) that are much shorter than the normal 4 minutes (blue detector) or 2 minutes (red detector). Each readout is stored in the raw data file as a group. The number of groups in a RAPID mode observation `.d0h` file is equal to the number of individual readouts.

The `.c3h` (special mode processing output) file contains two data groups. The number of pixels in each group is equal to the number of readouts (groups) in the original data. Group 1 of the `.c3h` file contains the summed flux values where the value of each pixel is the sum of all pixels from an original readout (i.e., pixel 1 contains the sum of all pixel values from readout 1, pixel 2 is the sum of all pixels from readout 2, etc.). Group 2 contains the sum of the corresponding statistical error values (in quadrature). The `.c3h` files effectively provide the light curve of the target for the length of the observation. See "Details of the FOS Pipeline Process" on page 235 for more details on special mode processing. The IRAF/STSDAS task to combine groups in such a dataset is **rcombine** (see Chapter 2).

## Spectropolarimetry Mode

Spectropolarimetry mode[3] is identified by an OPMODE value of "ACCUM" and a GRNDMODE value of "SPECTROPOLARIMETRY". The polarimetry data consist of a number of exposures (POLSCAN=16, 8, or 4) with the waveplate set at different angles and taken consecutively (within one orbit). The Wollaston prism splits the light beam into two spectra corresponding to the orthogonal directions of polarization. Hence, each exposure consists of the two orthogonal spectra obtained with a single waveplate angle. These spectra are deflected alternately onto the diode array, recorded as two pass directions, and stored as a single group in the raw data file. The first spectrum corresponds to the first pass direction (ordinary ray), the second to the second pass direction (extraordinary ray). The number of groups in the raw data file is equal to NREAD x POLSCAN. Thus, normally (for NREAD=1) there will be as many groups in the raw data file as the number of waveplate positions used in the observation. The number of POLSCAN positions (and therefore the total number of groups in the raw data file) may be 4, 8, or 16 depending on the number of polscans requested.

3. Further details concerning polarimetry datasets and their calibration procedures can be obtained from within IRAF by typing “help spec_polar opt=sys”.

# CHAPTER 13:
# FOS Planned vs. Executed Observations

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## Contents of Data Tapes

From either your data tape or the Archive you will receive various FITS files containing science data and other information. In the following we provide a description of what is stored where. The STSDAS routine for unpacking your data is **strfits** (see Chapter 3). The resulting files will have default extensions, as described in Table 13.1. The `.c*h` files represent different stages of the calibration process, which will be described in detail below. The easiest way to get a quick glance at your spectra is by using the IRAF/STSDAS routine **splot** or **fwplot** if you want to plot wavelength vs. flux (see Chapter 2).

**Table 13.1:** File Name Extensions

| Extension | File Contents |
|---|---|
| | ***Raw Data Files*** |
| `.shh/.shd` | Standard header packet |
| `.d0h/.d0d` | Science data image |
| `.q0h/.q0d` | Science data quality |
| `.d1h/.d1d` | Science trailer line |
| `.ulh/.uld` | Unique data log |
| `.x0h/.x0d` | Science header line |
| `.xqh/.xqd` | Science header line data quality |
| | ***Calibrated Data Files*** |
| `.c0h/.c0d` | Calibrated wavelengths |
| `.c1h/.c1d` | Calibrated fluxes |
| `.c2h/.c2d` | Propagated statistical error |
| `.c3h/.c3d` | Special statistics |
| `.c4h/.c4d` | Count rate |
| `.c5h/.c5d` | Flat-fielded object spectra |
| `.c6h/.c6d` | Flat-fielded sky spectra |
| `.c7h/.c7d` | Background spectra |
| `.c8h/.c8d` | Flat-fielded object minus smoothed sky spectra |
| `.cqh/.cqd` | Output data quality |

Detailed information about your data is given in several different places. We will give a brief overview of these sources here.

# Headers and Keywords

Header files provide most of the information needed to reduce FOS data. The headers are divided into groups of keywords that deal with a particular topic. A description of each keyword is often provided in the header itself. Table 13.2 is a short description of the different topics covered in the various header files. The header files used most often are the standard header packet (`.shh`), the science data header file (`.d0h`), and the calibrated science data header file (`.c1h`). Most of the information needed to understand the data is found in the header keywords that describe the general information and the processing and calibration information sections of the headers. Table 13.3 lists some of the important header keywords used to interpret FOS data.

**Table 13.2:** Types of Information in FOS Header Keywords

| Keyword Type | Information in Keywords | Source |
|---|---|---|
| | ***General Information*** | |
| General data | General structure information for data file in standard FITS style | All headers |
| Group Parameters: OSS | Acquisition data description, including time of acquisition (modified Julian date), maximum and minimum data values, and axes information | All headers |
| Group Parameters: PODPS | Observation type and ground-based GIM correction values from GIMP_CORR | Calibrated header files |
| Generic Conversion Keywords | Existence of science trailer line and reject array | `.d0h` |
| FOS Descriptor Keywords | Description of FOS file and GIM correction | All headers |
| COSTAR Keywords | Positions of the COSTAR FOS M1 mirror | `.shh` |
| | ***Engineering Information*** | |
| Time Conversion Keywords | Spacecraft and Universal time at start of observation | `.shh` |
| CDBS Keywords in SHP | Engineering data regarding temperatures, currents, and voltages at various points in the instrument | `.shh` |
| CDBS Keywords in UDL | Data acquisition details, such as number of channels used, value of magnetic field deflections used | `.ulh` |
| | ***Processing and Calibration Information*** | |
| Statistical Keywords | Processing information | `.shh`, `.d0h`, and calibrated data headers |
| Calibration Flags and Indicators | Type of observation and configuration of aperture, grating, and detector | `.d0h` and calibrated data headers |
| Calibration Reference Files & Tables | Reference files and tables for calfos processing (either used or to be used) | `.d0h` and calibrated data headers |
| Calibration Switches | Calibration steps for calfos processing (either used or to be used) | `.d0h` and calibrated data headers |
| Pattern Keywords | Magnetic field deflection pattern used in acquiring the data | `.d0h` and all calibrated data header files |
| Calibration Keywords | Observing time, user-supplied GIM offset table name, LIVETIME, DEADTIME, position angle of aperture, burst noise rejection limit | `.d0h` and calibrated data headers |
| Aperture Position | Aperture position in RA and Dec | `.d0h` and calibrated data headers |

| Keyword Type | Information in Keywords | Source |
|---|---|---|
| Exposure Information | Exposure information and commanded FGS lock | `.d0h` and calibrated data headers |
| | ***Observer-Supplied Observing Information from Phase II Proposal*** | |
| Support Schedule: Program Info | Information on cover page of proposal and type of output data requested by GO | `.shh` |
| Support Schedule: Flags and Indicators | Type of observation requested by GO, for example, the aperture, the detector, the number of channels, etc. | `.shh` |
| Proposal Info | Observing strategy, e.g., instrument configuration, target description, and information on flux, exposure, moving target, spatial scan etc. | `.shh` |
| Target and Proposal ID | Target and PEP information | `.shh` |
| | ***Observing Information Produced in TRANS Stage*** | |
| Support Schedule: Data Group II | Telescope pointing and instrument configuration on the sky, i.e., target RA and Dec and offset objects, position angle of diode array, OFFSET information, spacecraft velocity, guide stars, etc. | `.shh` |
| Onboard Ephemeris Model | Spacecraft ephemeris | `.shh` |

**Table 13.3:** FOS Header Keywords

| Keyword | Description and Comments |
|---|---|
| | ***General Information from Header File—usually .d0h or .c1h*** |
| GCOUNT | Number of groups in data file |
| YTYPE | Nature of observation, important for paired aperture observations. (Not real values in d0h file). Values are OBJ, BKG, or SKY |
| YPOS*n* | Location of diode center in Y-base units, of the *n*th group, useful for interpreting ACQ/BIN data. If there is only one group then YPOS is the Y-base of that one group. Not populated with real values in the .d0h file |
| YBASE | YPOS of group #1 |
| XBASE | XDAC units needed to center aperture on the diode array for group #1 |
| BUNIT | Flux units of the data. Values: COUNTS, COUNTS/SEC, ERGS/SEC/ CM^2/A, or ANGSTROM |
| FILLCNT | Number of sequences of filled data |
| ERRCNT | Number of sequences with bad data |
| INSTRUME | Instrument used for the observation. This will be FOS. |
| ROOTNAME | Rootname of the observation set. Will start with letter “y” |
| FILETYPE | Type of data in the file: SHP is science header packet, UDL is unique data log, SDQ is raw science data quality, WAV is wavelength, FLX is calibrated flux, ERR is calibrated flux error, MOD is CALFOS special mode processed data, SCI is object, sky, or background science data, OBJ is object data, BKG is background data, CDQ is calibration data quality, SKY is sky data, NET is sky-subtracted object data |

**Table 13.3:** FOS Header Keywords

| Keyword | Description and Comments |
|---|---|
| GRNDMODE | Ground software mode of FOS. Can be SPECTROSCOPY, TARGET ACQUISITION, IMAGE, RAPID-READOUT, SPECTRO-POLARIMETRY, or TIME-RESOLVED |
| DETECTOR | Detector in use for the observation. AMBER or BLUE |
| APER_ID | Aperture used for the observation; A-1 corresponds to the 4.3″, A-2 to the 0.5″ pair (square), A-3 to the 0.25 pair (square), A-4 to the 0.1 pair (square), B-1 to the 0.5″ (round), B-2 to the 0.3″ (round), B-3 to the 1.0″ (round), B-4 is blank, C-1 to the 1.0″ pair (square), C-2 to the 0.25″x2.0″ slit, C-3 to the 0.7″x2.0″ bar, and C-4 to the 2.0″ bar apertures respectively |
| POLAR_ID | Polarization waveplate used for the observation. A is the waveplate A, B is the waveplate B and C is no polarizer used (clear) |
| FGWA_ID | Filter and grating used for the observation. H*xx* means G*xx*0H filter, L15 means G160L, L65 means G650L, PRI means PRISM, and CAM means camera (mirror). |
| POLANG | Initial angular position of the polarizer in degrees |
| FCHNL | First diode used in observation (first diode in array is designated as zero) |
| NCHNLS | Number of diodes used in the observation, useful for interpreting ACQ/BIN data and exposure time. Usually 512 (except target acquisition and other specific modes, see below) |
| OVERSCAN | Number of overscans used in the observation, useful for interpreting ACQ/BIN data and exposure time. Usually 5 |
| NXSTEPS | Number of X substeps used in the observation, useful for interpreting ACQ/BIN data and exposure time. Usually 4 |
| MINWAVE | Minimum wavelength in Å. (Not populated in `.c0h` file) |
| MAXWAVE | Maximum wavelength in angstroms. (Not populated in `.c0h` file) |
| YFGIMPEN | Onboard GIM correction enabled. T or F |
| KYDEPLOY | COSTAR mirror deployment for the FOS. T or F |
| | ***Exposure Time Information—usually in .d0h or .c1h*** |
| FPKTTIME | Time of first data packet sent to the SDF, i.e., time at the *end* of the group exposure. The units are modified Julian date. Each group has its own unique FPKTIME |
| LPKTTIME | Time of the last data packet sent to the SDF. The units are modified Julian date. |
| DATE-OBS | FPKTTIME of group 1 converted to standard notation for date |
| TIME-OBS | FPKTTIME of group 1 converted to standard notation for time, truncated to integer value; thus these are only accurate to 1/8 of a second |
| EXPSTART | Exposure start time in modified Julian date |
| EXPOSURE | Exact exposure time per pixel in seconds for each group. Note that this keyword is not populated with real values in the d0h file |
| | ***Pattern Keywords for Exposure Times—usually in .c0h or .c1h*** |
| LIVETIME | Time, in units of 7.8125 microseconds, during which accumulator is open |
| DEADTIME | Time, in units of 7.8125 microseconds, in which accumulator is closed |

**Table 13.3:** FOS Header Keywords

| Keyword | Description and Comments |
|---|---|
| INTS | Number of repetitions of the live time/dead time cycle |
| YSTEPS | Number of Y substeps used in the observation. Usually 1 |
| NPAT | Number of patterns used per readout |
| SLICES | Number of repeats of the magnetic field deflection sequence. Usually 1 |
| NREAD | Number of readouts per memory clear. For the ACCUM mode this is usually the number of groups. For RAPID mode this is 1 |
| NMCLEARS | Number of memory clears per obs. 1 for ACCUM, number of groups for RAPID mode when NMCLEARS > 1 |
| | ***Aperture Orientation Information—usually .shh and .d0h of acquisition image*** |
| OPMODE | Operation mode of the FOS for the observation. Can be: ACQ, ACQ/BIN, ACQ/PEAK, ACQ/FIRMWARE, IMAGE, ACCUM, RAPID or PERIOD |
| PA_APER | Position angle of the aperture in degrees |
| RA_APER1 | RA of aperture center in degrees |
| DECAPER1 | Dec of aperture center in degrees |

The first thing you want to know about your observations is whether they executed as planned. If you are the principal investigator of a program, a look into the output of the RPS2 software from the preparation of your observations might be very helpful. A commonly available document for every HST program is the exposure log sheet, which you can retrieve from the PRESTO web page:

`http://presto.stsci.edu/public/propinfo.html`

In Figure 13.1 we show one exposure log sheet as an example. This will be used in the following to outline a few checks you can run on your data in order to assess whether what you see is what you wanted to get. In our example the FOS observations started with a four-stage ACQ/PEAK target acquisition at the beginning of the visibility period, followed by science observations using the FOS/RD detector with the G270H grating and the circular 1.0″ aperture. The investigators used the occultation time to execute a side switch from FOS/RD to FOS/BL, which takes about 50 minutes. Then, in exposure number 5, they re-acquired the target with a single-stage peak-up in order to insure good pointing accuracy and then continued their science observations, now using the G190H grating for a total of 100 minutes. Looking at the data files, one can find out that this long integration was split into three parts, filling the remainder of the re-acquisition orbit and the subsequent two orbits.

We will now first show how to find out whether the target acquisition succeeded and then point out some basic first checks of the science data. In order to check whether a target acquisition was successful you need to follow the step pattern of the acquisition and see whether the telescope zeroed in on the right object. We will describe here the two most commonly used FOS target acquisition methods, ACQ/BIN and ACQ/PEAK.

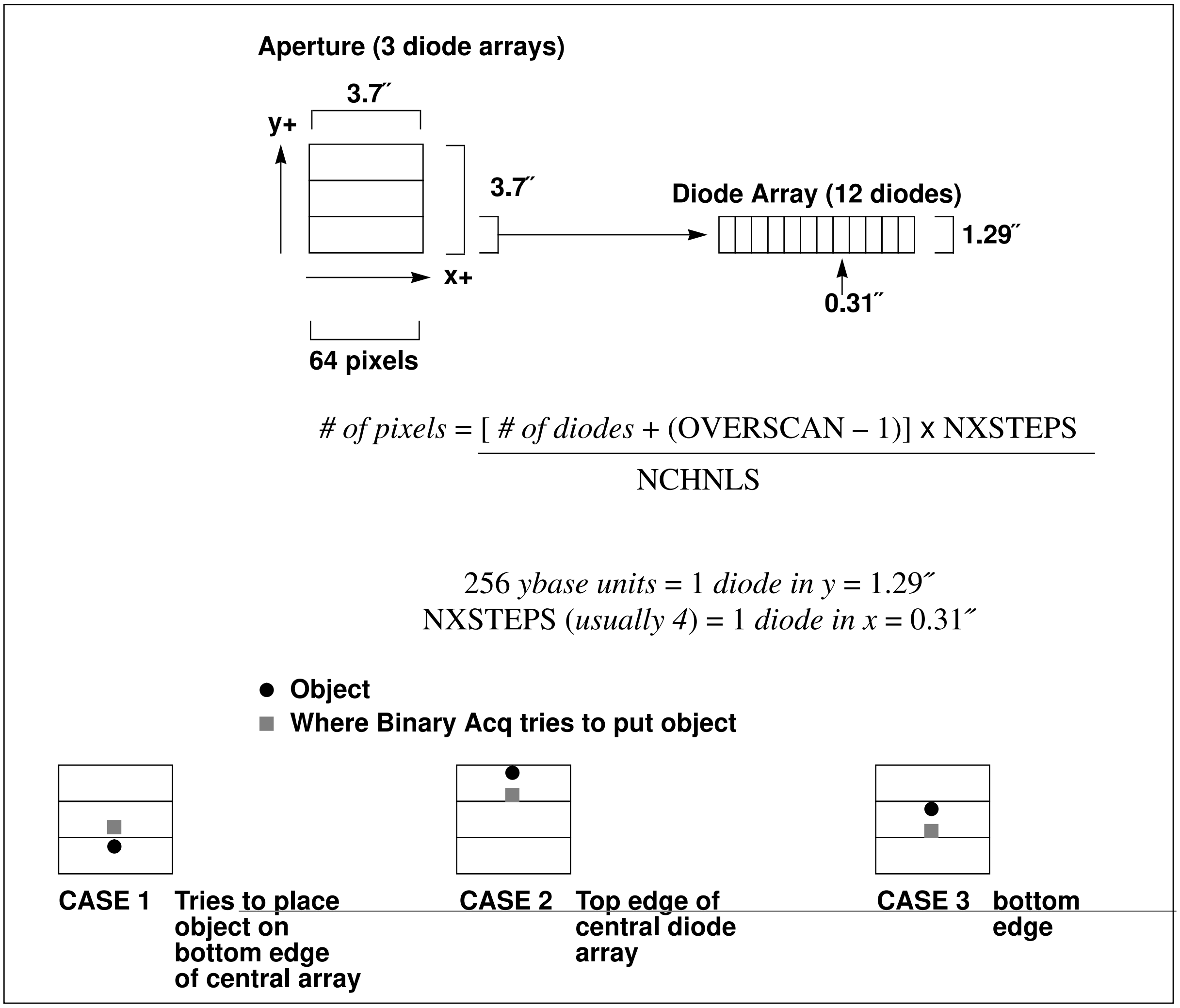
**Figure 13.1:** Sample Exposure Log Sheet

| Exposure Number | Target Name | Instr Config | Oper. Mode | Aper or FOV | Spectral Element | Central Waveln. | Optional Parameters | Num Exp | Time | Special Requirements |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ARP102B | FOS/RD | ACQ/ PEAK | 4.3 | MIRROR | | SCAN-STEP- Y=1.204 SEARCH-SIZE-X=1 SEARCH-SIZE-Y=3 | 1 | 1.4S | ONBOARD ACQ FOR 2 GROUP 1-7 WITHIN 3D GROUP 1-6 NO GAP |
| 2 | ARP102B | FOS/RD | ACQ/ PEAK | 1.0 | MIRROR | | SCAN-STEP- X=.602 SCAN-STEP- Y=.602 SEARCH-SIZE-X=6 SEARCH-SIZE-Y=2 | 1 | 2.0S | ONBOARD ACQ FOR 3 |
| 3 | ARP102B | FOS/RD | ACQ/ PEAK | 0.5 | MIRROR | | SCAN-STEP- X=0.30 SCAN-STEP- Y=0.30 SEARCH-SIZE-X=3 SEARCH-SIZE-Y=3 | 1 | 10S | ONBOARD ACQ FOR 3.5 |
| 3.5 | ARP102B | FOS/RD | ACQ/ PEAK | 0.3 | MIRROR | | SCAN-STEP- X=0.06 SCAN-STEP- Y=0.06 SEARCH-SIZE-X=5 SEARCH-SIZE-Y=5 | 1 | 10S | ONBOARD ACQ FOR 4 |
| 4 | ARP102B | FOS/RD | ACCUM | 1.0 | G270H | 2760 | | 1 | 33M | |
| 5 | ARP102B | FOS/BL | ACQ/ PEAK | 0.3 | MIRROR | | SCAN-STEP- X=0.06 SCAN-STEP- Y=0.06 SEARCH-SIZE-X=5 SEARCH-SIZE-Y=5 | 1 | 30S | ONBOARD ACQ FOR 6 |
| 6 | ARP102B | FOS/BL | ACCUM | 1.0 | G190H | 1950 | | 1 | 100M | |

# Binary Acquisition—ACQ/BIN

A binary target acquisition is performed with the 4.3″ aperture in several steps. Figure 13.2 shows a sketch illustrating this.

**Figure 13.2:** Binary Target Acquisition




First, the three thirds of the 4.3″ aperture (actual size now 3.7″ x 3.7″), which is three times as high as the diode array, are successively imaged onto the diode array in a search for the brightest third. The order in which the search is performed is center - lower - upper third. 256 y-base units represent the height of the diode array (1.29″). The first three groups in the multi-group ACQ/BIN spectrum will thus have YPOS entries of YPOS[1], YPOS[2] = YPOS[1] - 256, and YPOS[3] = YPOS[1] + 256. If the search algorithm finds an object in one of the three integrations, it will go back to this third of the aperture and then, by offsetting, try to place the object exactly on one edge of the diode array. In a successful approach it will try in successively smaller y-steps to place the object exactly on the edge, by trying to reach exactly half the count rate measured earlier, when the full flux of the object was projected onto the diode array. Since the gradient of the HST point-spread function is very steep, this produces a good measure of the y-position of the target. The y-position of the target is (YPOS[last group] - 128) - YPOS[1].

ACQ/BIN spectra have 64 pixels (12 diodes are read out). The central pixel is number 32. Just plotting the spectra shows the pixel location of the maximum and from this, you can calculate the x-offset from the center. In the x-direction, one diode (4 pixels) corresponds to 0.31″.

From the x- and y-offsets you can calculate the length of the required slew from original pointing guess to the estimated target position after acquisition. The statistical 1sigma uncertainty for ACQ/BIN is of order 0.1″. If your ACQ/BIN spectrum has 11 groups, it has failed. An example of the calculation of y- and x-offsets sketched above is available as a cookbook.

# Peak-up Acquisition—ACQ/PEAK

As for ACQ/BIN, the first stage of a peak-up (or peak-down) target acquisition is normally done in three steps with the 4.3″ aperture. The original target coordinates for the first stage are required to be accurate to about 1″, so that the object will fall within the 4.3″ aperture. After the first stage, which is a 1 x 3 step pattern in the y-direction, just as in ACQ/BIN, the subsequent stages of a peak-up sequence map the third of the aperture in which the target was found (i.e., the highest count rate measured). The second stage, in a 2 x 6 step pattern, using the 1.0″ aperture, traces the location of the source within the 1.3″ x 3.7″ area where it was found in the first stage. This narrows the area in which the target is located to the surface area of the 1.0″ aperture (one out of 12 spectra will have the most counts). The third stage of a peak-up sequence is normally a 3 x 3 point scan of the surface of the 1.0″ aperture, now using the 0.5″ aperture with a step size of about 0.3″. This will lead to a pointing accuracy of about 0.2″. If higher accuracy is needed, the surface area of the 0.5″ aperture has to be scanned with the 0.3″ aperture, possibly in two steps with decreasing step sizes. In order to convert FOS x,y coordinates into sky coordinates, you need to know the position angle of the aperture, which is documented in the header keyword PA_APER (see Chapter 5 of this book). Much information on target acquisition is given in the *FOS Instrument Handbook*. Additional details, such as the interpretation of how the telescope moves in a sky coordinate system when centering on the position of the highest observed count rates in the different acquisition stages, are available as a cookbook.

# Science Observations

After checking the target acquisition you will want to know whether your integration time requirements were actually fulfilled. The exposure log sheet (exposure number 4 in Figure 13.1) will only give a first estimate. The actual on-source integration times are stored in the headers of your science data (e.g., the `.c1h` and `.c0h` files), in the header keyword EXPTIME. If this should be much shorter than you planned, check whether the observation was interrupted by an earth occultation. In this case, the integration will have been resumed after re-acquisition of the guide stars after the occultation (Figure 13.1, exposure 6). In the example shown in Figure 13.1, the actual integration time with the G270H grating was 1190 seconds, filling the orbit up to the next earth occultation, plus 790 seconds in the next orbit.

In standard FOS ACCUM mode spectra the last group will contain the accumulated total integration on the target. Using the task **fwplot** you can easily check whether the spectrum shows a flux that is roughly like what you wanted. If your spectrum was split up into two or more parts, for example because it was observed in more than one satellite orbit due to earth occultations, you will obtain the sum of all integrations by adding up the last groups of all spectra of your target taken with the same instrument configuration (combination of detector, aperture, and disperser) .

In order to judge the quality of the spectra, including the quality of the calibration, the existence of artifacts, or the validity of specific features, you need detailed information on the single steps of the data calibration and on the instrument. Therefore, before we delve into more data analysis techniques, we describe in the next sections the data calibration, different checks you should perform, accuracies that you can expect for the FOS, and when and how to recalibrate your data, if necessary.

# Engineering Data

As of February 1995, the engineering data and jitter files, which are provided by the Observatory Monitoring System (OMS), are also shipped to observers. These can give valuable information, such as telescope performance during the observation and the position of the target within the aperture. See Chapter 5 for a description of these files.

CHAPTER 14:

# Calibrating FOS Data

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This chapter describes how data are processed in the standard pipeline calibration, through which all HST data pass. Included here will be details about each step in the calibration process, descriptions of the reference files and tables required by the **calfos** program, descriptions of the calibrated output files, and some information about polarimetric calibration.

## Pipeline Calibration Overview

As we mentioned earlier, data shipped to investigators or retrieved from the HST Data Archive are calibrated. The primary task for the calibration of FOS science spectra in the Routine Science Data Processing (RSDP) system (the *pipeline*) is **calfos**. The description of pipeline data processing presented in this chapter will follow the way **calfos** works. We will describe each step, the files used in that step, created files, potential problems that might occur, and how these problems can be identified and corrected. Figure 14.1 and Table 14.1 serve as an overview for the following descriptions.

**Figure 14.1:** Pipeline Processing by calfos

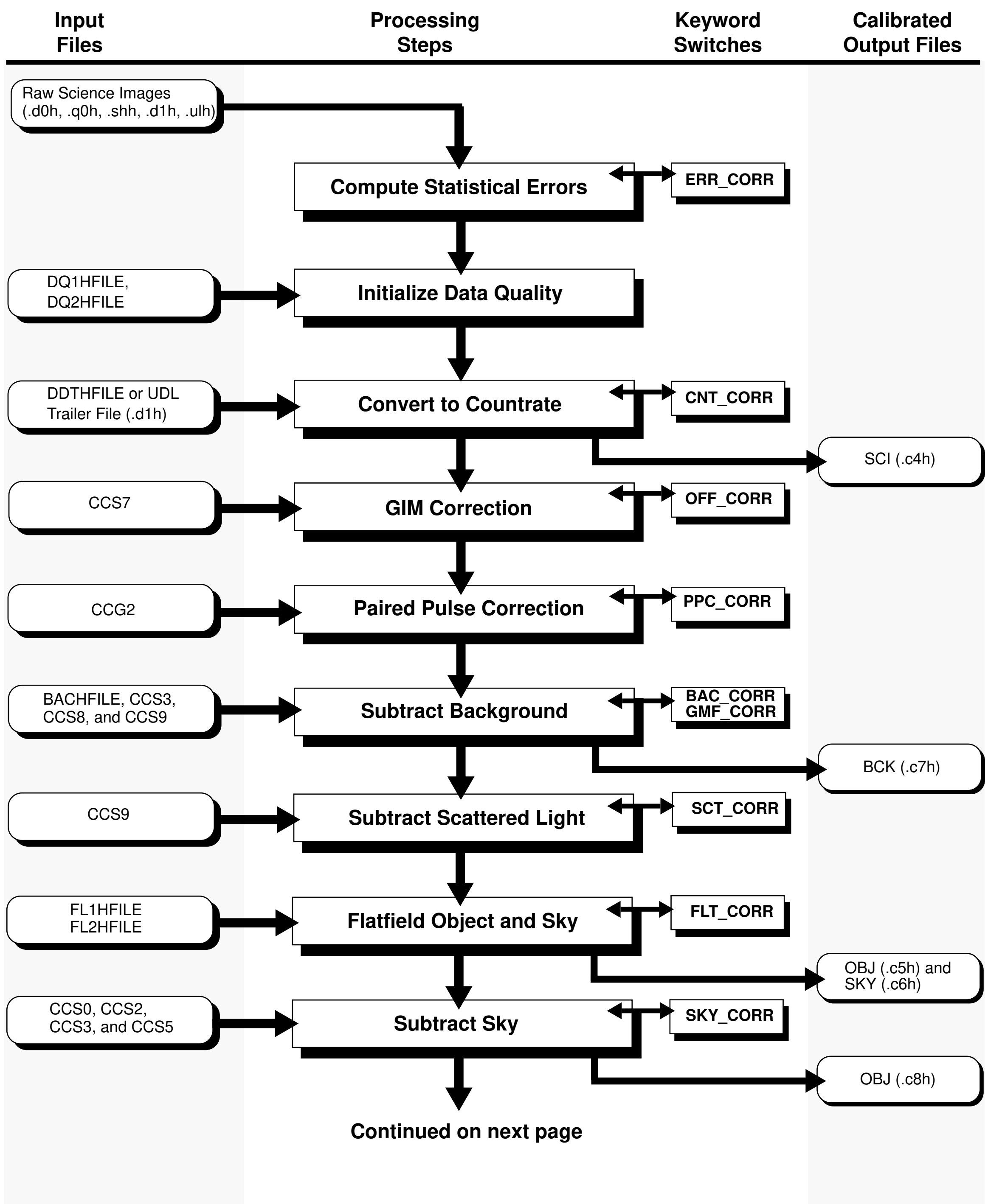


**Figure 14.1 (continued):** Pipeline Processing by calfos

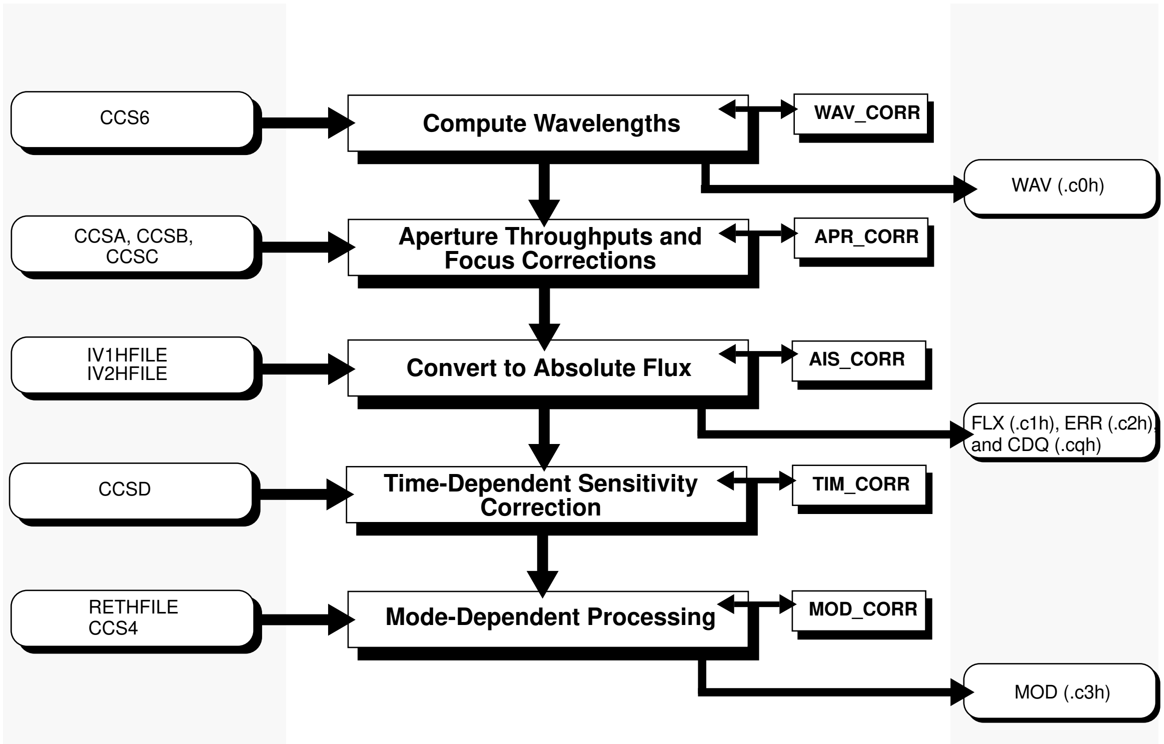



**Table 14.1:** Calibration Steps and Reference Files for FOS Pipeline Processing

| Switch | Processing Step | Reference File |
|---|---|---|
| ERR_CORR | Compute propagated error at each point in spectrum. Error file calibrated with science file and propagated statistical errors written to .c2h. | |
| CNT_CORR | Convert from raw counts to count rates by dividing each data point by exposure time and correcting for disabled diodes. Diode numbers are taken from ddthfile or from the unique data log. | `ddthfile` |
| OFF_CORR | Correct for image motion in the FOS X direction (dispersion) induced by magnetic field. Uses a model of the earth's magnetic field along with scale factors from table ccs7. This step should be applied for observations taken before April 4, 1993, after which the on-board GIM correction is used. | `ccs7` |
| PPC_CORR | Correct raw count rates for saturation in detector electronics using paired-pulse correction table (coccgr2). | `ccg2` |
| BAC_CORR | Correct for particle-induced background using default reference background (bachfile) if no background spectrum was obtained as part of the observation. | `bachfile` |
| GMF_CORR | If BAC_CORR is set to PERFORM, and the default background file (bachfile) is used, this file can be scaled to the expected mean count rate for the spacecraft geomagnetic position using the ccs8 reference table and subtracted from the count rate spectra by setting GMF_CORR to PERFORM. Scaled background is written to the .c7h file. | `ccs8` |

**Table 14.1:** Calibration Steps and Reference Files for FOS Pipeline Processing

| Switch | Processing Step | Reference File |
|---|---|---|
| SCT_CORR | Remove background scattered light. The scattered light is determined by calculating the mean value of diodes not illuminated by the selected grating. This mean is then subtracted from the observed spectrum. Un-illuminated diodes are found in the CCS9 reference table. | `ccs9` |
| FLT_CORR | Correct for diode to diode sensitivity variations by multiplying by the flatfield response file (fl1hfile). For paired aperture or spectropolarimetry observations, a second flatfield file is used. | `fl1hfile`, `fl2hfile` |
| SKY_CORR | If a sky spectrum was observed, the background is subtracted and the sky smoothed using a median and mean filter. Uses filter widths table (ccs3), aperture size table (ccs0), emission line positions (ccs2), and sky shift table (ccs5). | `ccs0`, `ccs2`, `ccs3`, `ccs5` |
| WAV_CORR | Compute vacuum wavelength scale for each object or sky spectrum using coefficients (ccs6). | `ccs6` |
| APR_CORR | Correct for relative aperture throughputs. Object data are normalized to the reference aperture used to derive the average inverse sensitivity used in AIS_CORR. This step is required if AIS_CORR is used. Object data are divided to correct for changes in aperture throughput due to changes in OTA focus. | `ccsa`, `ccsb`, `ccsc` |
| FLX_CORR | Convert from count rate to absolute flux units by multiplying by inverse sensitivity curve. Uses inverse sensitivity file (iv1hfile) or, for paired aperture or spectropolarimetry, file (iv2hfile). | `iv1hfile`, `iv2hfile` |
| AIS_CORR | Convert from count rate to absolute flux units by multiplying by inverse sensitivity curves. This step replaces FLX_CORR and is different in that an average inverse sensitivity, determined from calibration of all apertures, is used. APR_CORR must be performed for this step to have meaning. | `aishfile` |
| TIM_CORR | Correct for changes in instrument sensitivity over time by dividing the object data by an appropriate correction factor. | `ccsd` |
| MOD_CORR | Perform ground software mode dependent corrections for time-resolved, rapid readout, or spectropolarimetry observations. For RAPID, write total flux and sum of statistical errors to groups 1 and 2 of .c3h file. For PERIOD mode, write pixel-by-pixel averages of all slices to groups 1 and 2 of .c3h file. For spectropolarimetry, data from individual waveplate positions is used to make Stokes parameters I, Q, U, and V and linear and circular polarization position angle spectra. | `ccs4`, `rethfile` |

For the different corrections described above, **calfos** uses three different types of input files:

- Input data files: these are the observation data files, in Generic Edited Information Set (GEIS) format, i.e., a multi-group image.
- Reference files (GEIS format images).
- Reference tables (STSDAS tables).

# Input Files

Table 14.2 lists the science files that are used as input to **calfos**. These files are described briefly below.

**Table 14.2:** Observation Input Files for calfos

| File Extension | File Contents |
|---|---|
| .shh and .shd | Standard header packet |
| .ulh and .uld | Unique data log |
| .d0h and .d0d | Science data |
| .q0h and .q0d | Science data quality |
| .x0h and .x0d | Science header line |
| .xqh and .xqd | Science header line data quality |
| .d1h and .d1d | Science trailer line |
| .q1h and .q1d | Science trailer line data quality |

## Standard Header Packet

The standard header packet (SHP) contains the telemetry values for engineering data and some FOS-unique data. The engineering data include temperatures, currents, and voltages at various points in the instrument. The FOS-unique data varies depending on the onboard processing used for a given observation. The header packet also contains information used in the operation of the spacecraft, such as target name, position and velocity of the telescope, the right ascension and declination of the target, the sun, and the moon, and other proposal information used in the observation which was provided in phase II of the proposal process. The SHP files are identified by the extensions `.shh` and `.shd`.

## Unique Data Log

The unique data log (UDL) contains the mechanism control blocks used to control the entrance aperture, entrance port, polarizer, and filter grating wheel assembly. This file also contains the discriminator level, disabled diode table, serial engineering data, instrument configuration, and exposure parameters. The UDL files are identified by the extensions `.ulh` and `.uld`.

## Science Data Files

Science data files contain single-precision floating point values that represent the number of detected counts accumulated in each pixel. The number of data elements in the one-dimensional science data array depends on the observation mode. Specifically, the number of diodes, the number of substeps, the number of Y steps, and the number of repeats (sometimes called *slices* or *bins*) used in the observation. The maximum number of data elements is 12288. The associated header file also provides information on the different steps to be performed during pipeline calibration processing, and the reference files and tables to be used in the calibration. The uncalibrated science data files are identified by the extensions `.d0h` and `.d0d`.

## Science Header Line

The science header line (SHL) file is a one dimensional array with a length equal to a line of the science data. It contains a partial copy of the unique data log. The SHL files are identified by the extensions `.x0h` and `.x0d`.

## Science Trailer Line

The science trailer line (STL) file is also a one dimensional array containing the number of measurements rejected from the various combinations of X substeps, Y steps, repeats, etc. The rejection threshold is given in the unique data log header file under the keyword YNOISELM. The information in these files is used to compute the total effective exposure time per pixel which is later used to convert the counts into count rates. The STL files are identified by the extensions `.d1h` and `.d1d`.

## Data Quality Files

The science data files, science header line files, and the science trailer files have corresponding data quality files that contain the flags for bad or suspect data. These raw data quality files have quality flags as follows:

- *Good* data has the data quality flag =1.
- *Raw data dropouts* and *filled raw data* have the data quality flag =16.
- Data *failing a Reed-Solomon error check* has the data quality flag =100.

The data quality files are identified by the extensions `.q0h`, `.q0d`, `.xqh`, `.xqd`, `.q1h`, and `.q1d` corresponding to the science data, science header, and science trailer files.

# Reference Files

The reference files and tables are typically referred to by the name of the Calibration Data Base System (CDBS) reference relation that holds their names. The extensions of the reference tables and files are of the form .cy*n*, .r*n*h and .r*n*d where *n* represents a value from 0 to 9 and A to D (see Table 14.3). These files are maintained in the CDBS by STScI. STEIS maintains an updated catalog of these tables and files. In Chapter 4 we describe how to obtain these files.

Except for some spectropolarimetric reference files, which are twice this length (for two pass directions), all reference files contain a vector of length:

$$(N_{chan} + N_{over} - 1) \times N_x$$

Where

- $N_{chan}$ – is the number of channels observed (keyword NCHNLS).
- $N_{over}$ – is the number of channels multiplexed (keyword OVERSCAN).
- $N_x$ – is the number of substeps (keyword NXSTEPS).

Although the reference files can be generated for any combination of NXSTEPS, FCHNL (first channel), NCHNLS, and OVERSCAN, the routine calibration reference files have a length of 2064 pixels, corresponding to the standard keyword values:

- NXSTEPS = 4
- FCHNL = 0
- NCHNLS = 512
- OVERSCAN = 5

For other values of the above keywords **calfos** interpolates from the standard reference files. In some cases (non-standard NXSTEPS and OVERSCAN), the inverse sensitivity files and flatfields must be resampled before **calfos** will run correctly.

# Reference Tables

The CDBS relations for the FOS reference files and reference tables are described below. Note that these are relations that point to the reference files and tables: they do not contain the data used.

- **cyccs0r:** This table is used to determine the aperture area for paired apertures. If STEP-PATT=STAR-SKY is used, it is only for sky subtraction.
- **cyccs1r:** This table is used to determine which aperture (UPPER or LOWER) of a paired aperture was used for observing an object or sky spectrum.

**Table 14.3:** Reference Tables and Files Required by calfos

| Header Keyword | Data Base Relation | Filename Extension | File Contents |
|---|---|---|---|
| CCS0 | cyccs0r | `.cy0` | Aperture areas |
| CCS1 | cyccs1r | `.cy1` | Aperture positions |
| CCS2 | cyccs2r | `.cy2` | Sky emission line positions |
| CCS3 | cyccs3r | `.cy3` | Sky and background filter widths |
| CCS4 | cyccs4r | `.cy4` | Polarimetry parameters |
| CCS5 | cyccs5r | `.cy5` | Sky shift parameters |
| CCS6 | cyccs6r | `.cy6` | Wavelength dispersion coefficients |
| CCS7 | cyccs7r | `.cy7` | GIM correction scale factors |
| CCS8 | cyccs8r | `.cy8` | Predicted background (count rate) |
| CCS9 | cyccs9r | `.cy9` | Un-illuminated diodes for scattered light correction |
| CCSA | cyccsar | `.cya` | OTA focus positions for aperture throughputs |
| CCSB | cyccsbr | `.cyb` | Aperture throughput coefficients |
| CCSC | cyccscr | `.cyc` | Throughput corrections versus focus |
| CCSD | cyccsdr | `.cyd` | Instrument sensitivity throughput correction factors |
| CCG2 | coccg2r | `.cmg` | Paired-pulse coefficients |
| BACHFILE | cybacr | `.r0h` & `.r0d` | Default background file (count rate) |
| FL*n*HFILE | cyfltr | `.r1h` & `.r1d` | Flatfield file |
| IV*n*HFILE | cyivsr | `.r2h` & `.r2d` | Inverse sensitivity file (ergs $cm^{-2}$ $Å^{-1}$ $count^{-1}$ diode)[a] |
| RETHFILE | cyretr | `.r3h` & `.r3d` | Retardation file for polarimetry data |
| DDTHFILE | cyddtr | `.r4h` & `.r4d` | Disabled diode file |
| DQ*n*HFILE | cyqinr | `.r5h` & `.r5d` | Data quality initialization file |
| AISHFILE | cyaisr | `.r8h` & `.r8d` | Average inverse sensitivity file |

a. Note that all references to inverse sensitivity, IVS, in the version 6 *FOS Instrument Handbook* contain the per diode component of this definition implicitly. The meaning of IVS is identical in both this document the *FOS Instrument Handbook*.

- **cyccs2r:** Regions of the sky spectrum known to have emission lines. These regions are not smoothed before the sky is subtracted from the object spectrum.

The cyccs2r table values have not been confirmed after science verification (SV). It does not affect any data reduction step since there have been no GO sky observations.

- **cyccs3r:** Filter widths used for smoothing the sky or background spectra.
- **cyccs4r:** Polarimetry information regarding waveplate pass direction angles, initial waveplate position angles, the pixel number at which the wavelength shift between the two pass directions is to be determined for computing the merged spectrum, and the phase and amplitude coefficients for correction of polarization angle ripple.
- **cyccs5r:** The shift in pixels to be applied to the sky spectrum before subtraction.
- **cyccs6r:** Dispersion coefficients to generate wavelength scales. There is one entry for each detector, disperser, aperture, and polarizer combination.
- **cyccs7r:** GIM correction scale factors used to scale the modeled shift of the spectrum due to the earth's magnetic field.
- **cyccs8r:** Predicted background count rates as a function of geomagnetic position used to scale the background reference file.
- **cyccs9r**: Un-illuminated diode ranges for each detector and grating combination. Used to determine the background scattered light.
- **cyccsar**: List of OTA focus positions versus time. Used to correct for aperture sensitivity dependent on focus position.
- **cyccsbr**: Coefficients to normalize aperture throughputs to the reference aperture used to determine the average inverse sensitivity calibration.
- **cyccscr**: Throughput corrections versus focus.
- **cyccsdr**: Throughput correction factors to account for changes in instrument sensitivity over time.
- **coccg2r:** Paired pulse correction table used to correct for non-linear response of the diode electronics. Both detectors have the same correction constants, which are time independent.
- **cybacr:** This relation is for the background reference files. For each detector there is one file that is used as a default background count rate in the event no background spectra were observed.
- **cyfltr:** This relation is for the flatfield reference files. These files are used to remove the small scale diode and photocathode non-uniformities. There is one file for each detector, disperser, aperture, and polarizer combination.
- **cyivsr:** This relation is for inverse sensitivity reference files. These files are used to convert corrected count rates to absolute flux units. There is one file for each detector, disperser, aperture and polarizer combination. The best inverse sensitivity file suitable for a given observation can be found using

the StarView calibration screens (see “Tutorial: Retrieving Calibration Reference Files” on page 103) or by checking the information on inverse sensitivity files on STEIS which are updated with each delivery of new files. Figures 14.2 and 14.3 show the pre-COSTAR inverse sensitivity for the most commonly used gratings for both detectors. The new post-COSTAR sensitivity curves are plotted in Figures 14.4 and 14.5.

**Figure 14.2:** Pre-COSTAR Inverse Sensitivity Reference Files for Blue High Dispersion Gratings

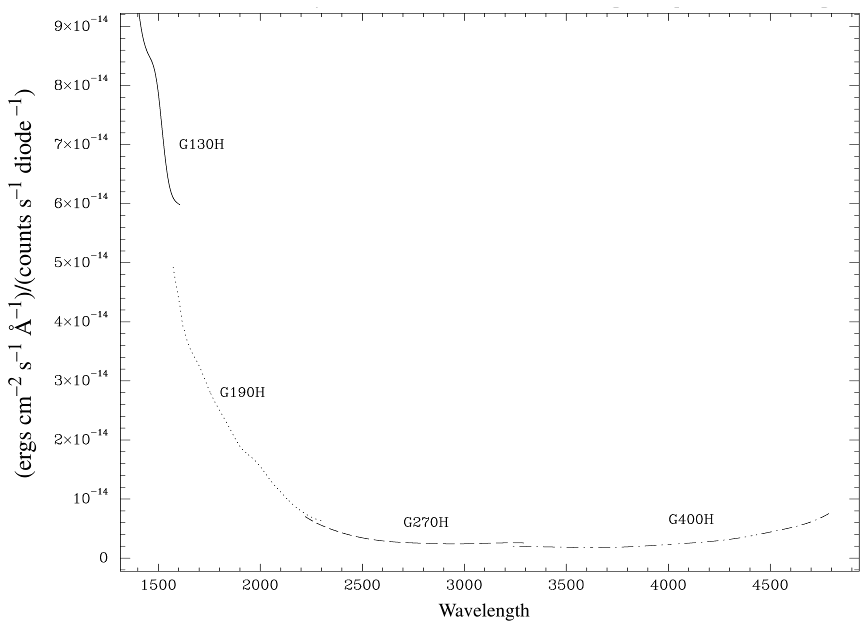


**Figure 14.3:** Pre-COSTAR Inverse Sensitivity Reference Files for Red High Dispersion Gratings

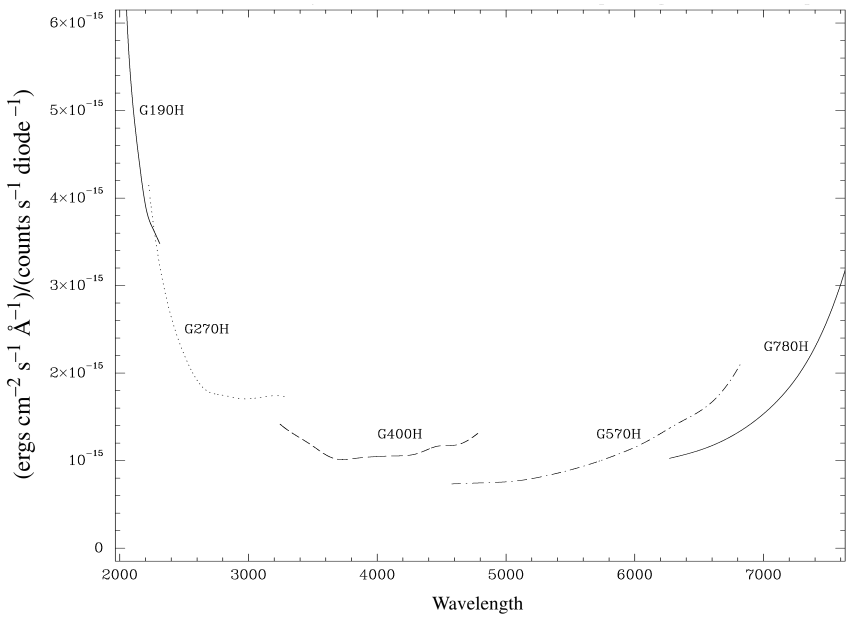



**Figure 14.4:** Cycle 4 Post-COSTAR Sensitivity Curves for High Dispersion Gratings

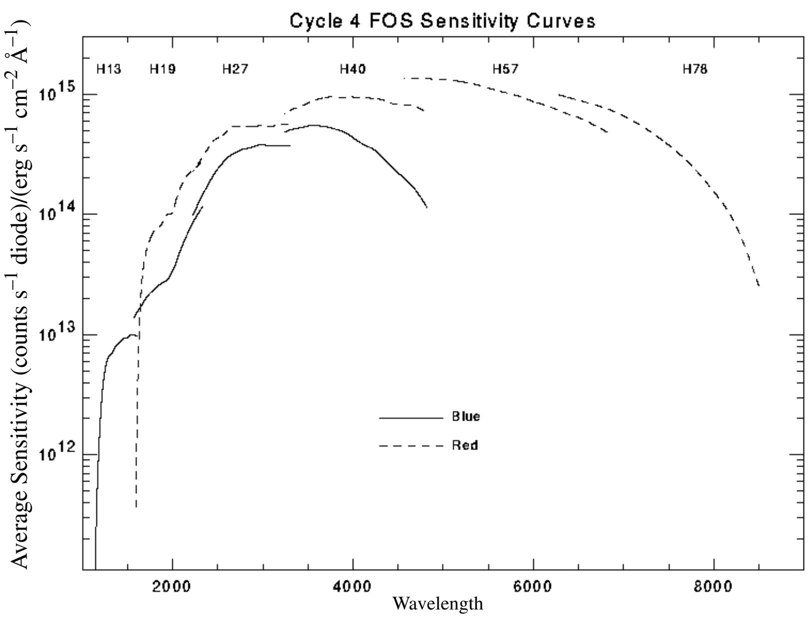
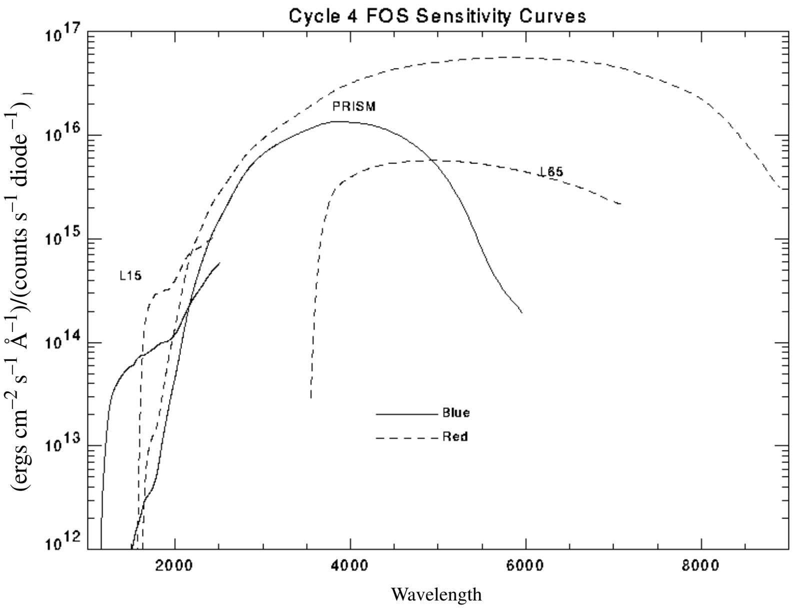
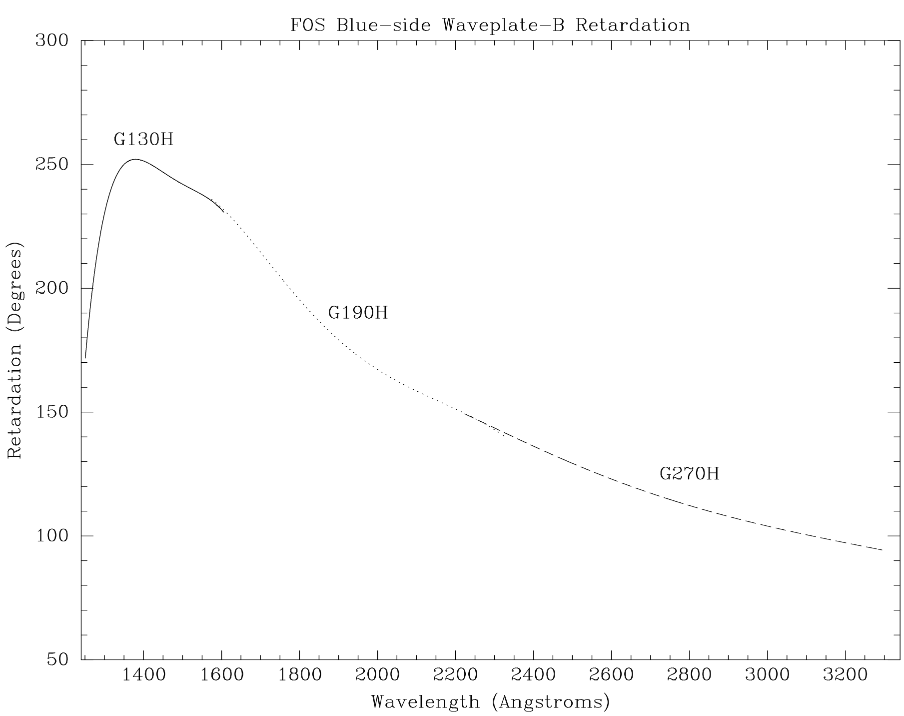


**Figure 14.5:** Cycle 4 Post-COSTAR Sensitivity Curves for Low Dispersion Gratings




- **cyretr:** This relation is for retardation reference files used for spectropolarimetric data. The files are used to create the observation matrix $f(w)$. There is one file for each detector, disperser, and polarizer combination. The three available retardation files for the blue detector and waveplate B are plotted in Figure 14.6 with the appropriate grating shown.

**Figure 14.6:** Retardation Reference Files



- **cyddtr:** This is the relation for the disabled diode files. The table is used only if the keyword DEFDDTBL = F in the `.d0h` file. The disabled diode information is also contained in the `.ulh` file. The disabled diode table is updated and information on this is found on STEIS. The total number of disabled blue diodes is 26 and disabled red diodes is 15, as of June 1995. Note that the diodes in the Tables 14.4 and 14.5 are numbered such that the first diode in the diode array is 0 and the last diode is 511. For use in IRAF and STSDAS, the diode number would be the diode number in the table + 1.
- **cyaisr**: This is the relation for the average inverse sensitivity reference files. These files are used to convert corrected count rates to absolute flux units. There is one file for each detector and disperser combination.

**Table 14.4:** Blue Detector Disabled Diodes as of August 1995

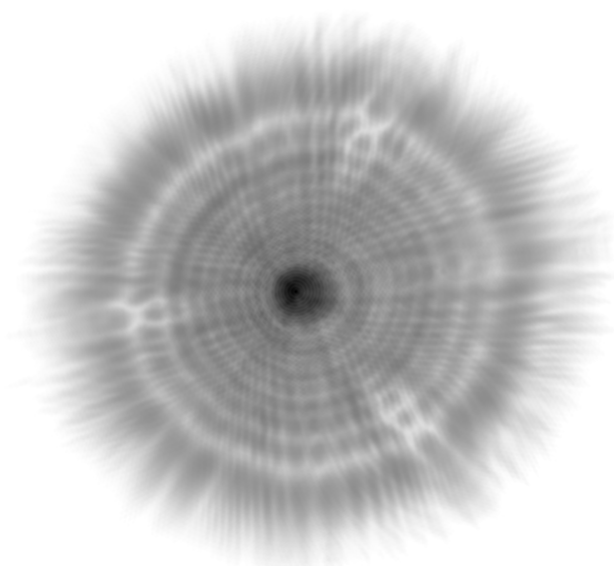
| DISABLED Dead Channels | DISABLED Noisy Channels | DISABLED Cross-Wired Channels | ENABLED But Possibly Noisy |
|---|---|---|---|
| 49 | 31 | 47 | 8 |
| 101 | 73 | 55 | 138 |
| 223 | 144 | | 139 |
| 284 | 201 | | 209/210 |
| 292 | 218 | | 381 |
| 409 | 225 | | 421 |
| 441 | 235 | | 426 |
| 471 | 241 | | |
| | 268 | | |
| | 398 | | |
| | 415 | | |
| | 427 | | |
| | 451 | | |
| | 465 | | |
| | 472 | | |
| | 497 | | |
| 8 | 16 | 2 | 7 |

- **cypsf:** This is the relation for the monochromatic pre-COSTAR point spread functions for the FOS, covering the wavelength range 1200–5400 Å for the blue side and 1600–8400 Å for the red side. These PSFs were modeled using the TIM software. In Figure 14.7, a sample blue side FOS PSF at 1400 Å is shown.

**Table 14.5:** Red Detector Disabled Diodes as of August 1995

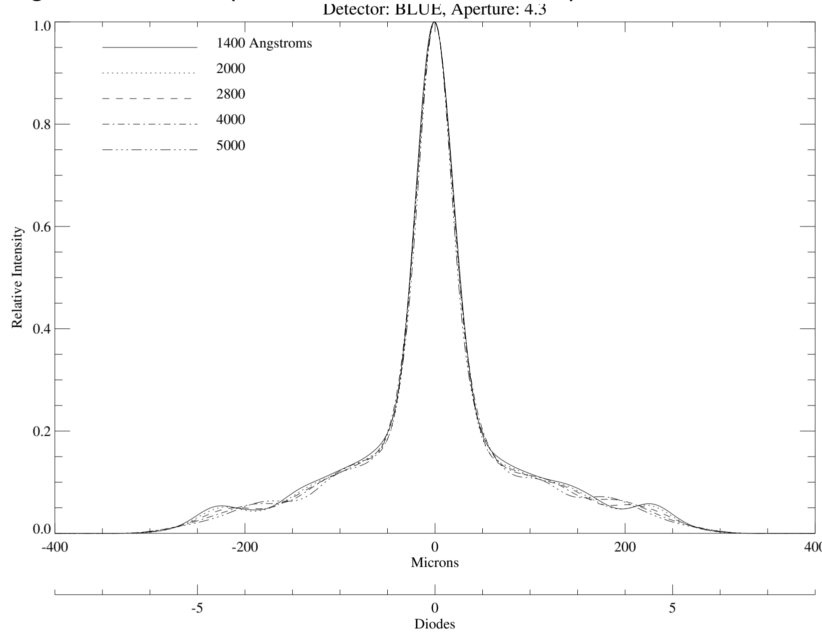
| DISABLED Dead Channels | DISABLED Noisy Channels | ENABLED But Possibly Noisy |
|---|---|---|
| 2 | 110 | 97 |
| 6 | 189 | 114/115 |
| 29 | 285 | 116 |
| 197 | 380 | 142 |
| 212 | 381 | 153 |
| 308 | 405 | 174 |
| 486 | 409 | 225 |
| | 412 | 258/259 |
| | | 261 |
| | | 285 |
| | | 289 |
| | | 410 |
| 7 | 8 | 14 |

**Figure 14.7:** Example of a Pre-COSTAR Point Spread Function for the FOS



- **cylsf:** This is the relation for the monochromatic pre-COSTAR line spread functions for all of the non-occulting FOS apertures computing using the PSFs in cypsf. Figure 14.8 shows a sample monochromatic FOS LSF for the blue side 4″.3 aperture. LSFs are available at each PSF wavelength.

**Figure 14.8:** Example of a Pre-COSTAR Line Spread Function for the FOS




- **cyqinr:** This is the relation for the data quality initialization files. These files are used to flag intermittent or noisy diodes, *but have not been kept up to date.*

# Details of the FOS Pipeline Process

This section describes in detail the pipeline calibration (**calfos**) procedures. Each step of the processing is selected by the values of keyword *switches* in the science data header file. All FOS observations undergo pipeline processing to some extent. Target acquisition and IMAGE mode data are processed only up to step 6 (paired pulse correction) but are not GIM corrected. ACCUM data are processed up to step 14 (absolute flux calibration) and RAPID, PERIOD, and POLARIMETRY data are processed up to step 15 (special mode processing). The steps in the FOS calibration process are:

1. Read the raw data.
2. Calculate statistical errors (ERR_CORR).
3. Initialize data quality.
4. Convert to count rates (CNT_CORR).
5. Perform GIM correction (OFF_CORR).
6. Do paired-pulse correction (PPC_CORR).
7. Subtract background (BAC_CORR).
8. Subtract scattered light (SCT_CORR).

9. Do flatfield correction (FLT_CORR).
10. Subtract sky (SKY_CORR).
11. Correct aperture throughput and focus effects (APR_CORR).
12. Compute wavelengths (WAV_CORR).
13. Correct time-dependent sensitivity variations (TIM_CORR).
14. Perform absolute calibration (FLX_CORR); superseded by AIS_CORR.
15. Do special mode processing (MOD_CORR).

These steps are described in detail in the following sections. A basic flowchart is provided in Figure 14.1 on page 222.

Note that AIS_CORR overrides FLX_CORR, if both are set to PERFORM.

## Reading the Raw Data

The raw data, stored in the `.d0h` file, are the starting point of the pipeline data reduction and calibration process. The raw science data are read from the `.d0h` file and the initial data quality information is read from the `.q0h` file. If science trailer (`.d1h`) and trailer data quality (`.q1h`) files exist, these are also read at this time.

## Calculating Statistical Errors (ERR_CORR)

The noise in the raw data is photon (Poisson) noise and errors are estimated by simply calculating the square root of the raw counts per pixel. An error value of zero is assigned to filled data, i.e., pixels that have a data quality value of 800.[1] For all observing modes except polarimetry, an error value of zero is also assigned to pixels that have zero raw counts. Polarimetry data that have zero raw counts are assigned an error value of one.

From this point on, the error data are processed in lock-step with the spectral data, except that errors caused by sky and background subtraction, as well as those from flatfields and inverse sensitivity files, are ignored. At the end of the processing, the calibrated error data will be written to the `.c2h` file.

## Data Quality Initialization

The starting point of the data quality information is the data quality values from the spacecraft as recorded in the `.q0h` file. This step of the processing adds values from the data quality reference files to the initial values in the `.q0h` file.

1. Data quality values are described in Table 17.3 on page 288.

The routine uses the data quality initialization reference file DQ1HFILE listed in the `.d0h` file. A second file, DQ2HFILE, is necessary for paired-aperture and spectropolarimetry observations. These reference files contain flags for intermittent noisy and dead channels (data quality values 170 and 160, respectively). The data quality values are carried along throughout the remaining processing steps where subsequent routines will add values corresponding to other problem conditions. *Only the highest (most severe) data quality value is retained for each pixel.* At the end of the processing the final data quality values will be written to the `.cqh` file.

---

The noisy and dead channels in the data quality files could be out of date, but the dead diode tables have the most up-to-date list of dead and noisy diodes.

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## Conversion to Count Rates (CNT_CORR)

At this step, the raw counts per pixel are converted to count rates by dividing by the exposure time of each pixel. Filled data (data quality = 800) are set to zero. A correction for disabled diodes is also included at this point. If the keyword DEFDDTBL in the `.d0h` file is set to TRUE, the list of disabled diodes is read from the unique data log (`.ulh`) file. Otherwise the list is read from the disabled diode reference file, DDTHFILE, named in the `.d0h` file. The DDTHFILE is more commonly used for the disabled diode information.

The actual process by which the correction for dead diodes is accomplished is as follows. First, recall that because of the use of the OVERSCAN function, each pixel in the observed spectrum actually contains contributions from several neighboring diodes (see “Science Data Acquisition” on page 206 for more details). Therefore, if one or more particular diodes out of the group that *fed* a given output pixel is dead or disabled, there will still be some amount of signal due to the contribution of the remaining live diodes in the group. Therefore we can correct the observed signal in that pixel back to the level it would have had if all diodes were live; to do this, we divide by the relative fraction of live diodes. The corrected pixel value is zero if all the diodes that contribute to that pixel are dead or disabled, otherwise, the value is given by the equation:

$$corr = obs\frac{total}{(total - dead)}$$

Where:

- *corr* – is the corrected pixel value.
- *obs* – is the observed pixel value.
- *total* – is the total number (live + dead) of diodes.
- *dead* – is the number of dead or disabled diodes.

This correction (to the signal and its associated error) is applied at the same time the raw data are divided by exposure time. If the fraction of dead diodes for a given pixel exceeds 50%, then a data quality value of 50 is assigned. If all of the diodes for a given pixel are dead, both the data and error values are set to zero and a data quality value of 400 is assigned.

The count rate spectral data are written to the `.c4h` file at this point. Note that the S/N in a given pixel is appropriate to the actual observed count rate.

## GIM Correction (OFF_CORR)

Data obtained prior to April 5, 1993, do not have an onboard geomagnetic-induced image motion (GIM) correction applied, and therefore require a correction for GIM in the pipeline calibration. Note that there are some observations obtained after April 5, 1993, that do *not* have onboard GIM correction, because the application of the onboard GIM correction depended on when the proposal was completely processed. The GIM correction is determined by scaling a model of the strength of the geomagnetic field at the location of the spacecraft. The model scale factors are read from the CCS7 reference table. The correction is applied to the spectral data, the error data, and the data quality values.

A unique correction is determined for each data group based on the orbital position of the spacecraft at the mid-point of the observation time for each group. While the correction is calculated to sub-pixel accuracy, it is applied as an integer value and is therefore accurate only to the nearest integral pixel. This is done to avoid resampling the data thereby losing information. Furthermore, the pipeline correction is applied only in the x direction (i.e., along the diode array).

The correction is applied by simply shifting pixel values from one array location to another. As a typical example, if the amount of the correction for a particular data group is calculated to be +2.38 pixels, the data point originally at pixel location 1 is shifted to pixel 3, pixel 2 shifted to pixel 4, pixel 3 to pixel 5, and so on. Pixel locations at the ends of the array that are left vacant by this process (e.g., pixels 1 and 2 in the example above) are set to a value of zero and are assigned a data quality value of 700.

Special handling is required for data obtained in ACCUM mode since each data frame contains the sum of all frames up to that point. In order to apply a unique correction to each frame, data taken in ACCUM mode are first *unraveled* into separate frames. Each frame is then corrected individually, and the corrected frames are recombined.

Target acquisition data, image mode data, and polarimetry data are not GIM corrected during the pipeline processing.

The onboard GIM correction is applied on a finer grid and in both the direction of the diode array and in the perpendicular direction. In the direction of the diode array the onboard GIM correction is applied in units of 1/32 of the width of the diodes and in units of 1/256 of the diode height in the direction perpendicular to the diode array.

The onboard GIM correction is calculated and applied every 30 seconds, and is applied to all observations except for ACQ/PEAK observations.

## Paired Pulse Correction (PPC_CORR)

This step corrects the data for saturation in the detector electronics. The dead time constants $q_0$, $q_1$, and F are read from the reference table CCG2. Currently the values of these dead time constants in the CCG2 table are $q_0 = 9.62\text{e-}6$ seconds, $q_1 = 1.826\text{e-}10$ $\text{sec}^2$/counts, and F = 52,000 counts per second. The following equation is used to estimate the true count rate:

$$x = \frac{y}{(1 - yt)}$$

Where:

- $x$ – is the true count rate.
- $y$ – is the observed count rate.
- $t$ – is $q_0$ for y less than or equal to F.
- $t$ – is $q_0 + q_1 * (y\text{-}F)$ for y greater than F.

Currently the values of these different saturation limits in the CCG2 table are as follows:

- Observed count rates greater than the saturation limit of 57,000 counts per second (and recorded in the **calfos** processing log) are set to zero and assigned a data quality value of 300.
- All observed count rates that are between this severe saturation limit and 10 counts/second are corrected, but those lying between the predefined limits of large (55,000 counts/second) and severe saturation (57,000 counts/second) are assigned a data quality value of 190.
- Those that lie between the limits of moderate (52,000 counts/second) and large (55,000 counts/second) saturation are assigned a data quality value of 130, and the paired pulse correction is applied.
- Count rates between the threshold value (10 counts/second) and 52,000 counts/second have the paired pulse correction applied.
- Data with count rates below this threshold value (10 counts/second) do not have any paired-pulse correction.

## Background Subtraction (BAC_CORR)

This step subtracts the background (i.e., the particle-induced dark current) from object and sky (if present) spectra. If no background spectrum was obtained with the observation, a default background reference file, BACHFILE, which is scaled to a mean expected count rate based on the geomagnetic position of the spacecraft at the time of the observation, is used. The scaling parameters are stored in the reference table CCS8. The scaled background reference spectrum is written to the `.c7h` file for later examination.

If an observed background is used, it is first repaired; bad points (i.e., points at which the data are flagged as lost or garbled in the telemetry process) are filled by linearly interpolating between *good neighbors*. Next, the background is smoothed with a median filter, followed by a mean filter. The median and mean filter widths are stored in reference table CCS3. No smoothing is done to the background reference file, if used, since the file is already a smoothed approximation to the background. Spectral data at pixel locations corresponding to repaired background data are assigned a data quality value of 120. Finally, the repaired background data are subtracted.

Although this is called background subtraction, it is really a *dark count* subtraction.

## Scattered Light Correction (SCT_CORR)

This step removes scattered light present in the object data for certain detector and grating modes. Some detector and grating combinations do no fully illuminate all the science diodes. For these combinations, the *dark* diodes can be used to measure the scattered light illuminating the diodes. For the valid combinations, the average count rate for these diodes are determined and subtracted from the whole data array, including the *dark* pixels. The **calfos** task will tell you (via the standard output) if it performs this step, along with the subtracted value; this information is also available in the trailer file if you have a dataset from the pipeline.

## Flatfield Correction (FLT_CORR)

This step removes the diode-to-diode sensitivity variations and fine structure (typically on size scales of ten diodes or less) from the object, error, and sky spectra by multiplying each by the inverse flatfield response as stored in the FL1HFILE reference file. A second flatfield file, FL2HFILE, is required for paired aperture or spectropolarimetry observations. No new data quality values are assigned in this step.

## Sky Subtraction (SKY_CORR)

If the sky was observed, the flatfielded sky spectrum is repaired in the same fashion as described above for an observed background spectrum. The spectrum is then smoothed once with a median filter and twice with a mean filter, except in regions of known emission lines, which are masked out. The CCS2 reference table contains the pairs of starting and ending pixel positions for masking the sky emission lines. The sky spectrum is then scaled by the ratio of the object and sky aperture areas, and then shifted in pixel space (to the nearest integer pixel) so that the wavelength scales of the object and sky spectra match. The sky spectrum is then subtracted from the object spectra and the resulting sky-subtracted object spectrum is written to the `.c8h` file. Pixel locations in the sky-subtracted object spectrum that correspond to repaired locations in the sky spectrum are assigned a data quality value of 120.

This routine requires table CCS3 containing the filter widths, the aperture size table CCS0, the emission line position table CCS2, and the sky shift table CCS5.

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This observation mode has never been used as half the integration time must be spent on the sky. Since there have been no GO science observations for the sky, the CCS2 table values have not been confirmed.

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Note that—especially for extended objects—paired aperture observations can be obtained in the so-called "OBJ-OBJ" mode, in which no sky subtractions are performed.

## Computing the Wavelength Scale (WAV_CORR)

A *vacuum* wavelength scale is computed for each object or sky spectrum. Wavelengths are computed using dispersion coefficients corresponding to each grating and aperture combination stored in reference table CCS6. The computed wavelength array is written to the `.c0h` file.

For the gratings the wavelengths are computed as follows:

$$\lambda(\text{Å}) = \sum_{p=0}^{3} l(p) \times x^p$$

For the prism, wavelengths are computed as:

$$\lambda(\text{Å}) = \sum_{p=0}^{4} \frac{l(p)}{(x - x_0)^p}$$

Where:

- $l(p)$ – are the dispersion coefficients in table CCS6.
- $x$ – is the position (in diode units) in the object spectrum, where the first diode is indexed as 0.
- $x_0$ – is a scalar parameter also found in table CCS6.

Note that the above equations determine the wavelength at each diode. This must be converted to pixels using NXSTEPS. For example, if NXSTEPS=4, the values for $x$ are given as 0, 0.25, 0.5, 0.75, 1, etc., for pixels 1, 2, 3, 4, 5, etc.

For multigroup data, as in either rapid-readout or spectropolarimetry mode, there are separate wavelength calculations for each group. These wavelengths may be identical or slightly offset, depending on the observation mode.

## Aperture Throughput Correction (APR_CORR)

This calibration step consists of two parts: normalizing throughputs to a reference aperture and correcting throughputs for focus changes. Both steps are relevant only if the average inverse sensitivity files are used, see AIS_CORR.

Each aperture affects the throughput of light onto the photocathode. To prepare the object data for absolute flux calibration, the object data must be normalized to the throughput as would be seen through a pre-determined reference aperture. The normalization is calibrated as a second-order polynomial and is a function of wavelength. The polynomial is evaluated over the object's wavelength range and divided into the object data. The coefficients are found in the CCSB reference table.

Once the object data has been normalized, the throughput compensates for variations in sensitivity due to focus changes. The CCSA table contains a list of dates and focus values. The sensitivity variation is modeled as a function of wavelength and focus, the coefficients of which are found in the CCSC table. This model is evaluated and divided into the object data.

## Absolute Flux Calibration

This step multiplies object (and error) spectra by the appropriate inverse sensitivity vector to convert from count rates per diode to absolute flux units (erg $s^{-1}$ $cm^{-2}$ $Å^{-1}$). Two different methods of performing this calibration have been used. The pipeline has used the so-called FLX_CORR method from the time of HST launch through 1995. The pipeline processing method, for non-polarimetric observations, is expected to be changed to the so-called AIS_CORR method in 1996. AIS_CORR is also available, and the preferred method, to re-calibrate any future non-polarimetric FOS observations. Spectropolarimetry will continue to be processed via the FLX_CORR method.

***FLX_CORR:*** The inverse sensitivity data are read from the IV1HFILE reference file. A second inverse sensitivity file, IV2HFILE, is required for paired-aperture or spectropolarimetry observations. Points where the inverse sensitivity is zero (i.e., not defined) are flagged with a data quality value of 200. The calibrated spectral data are written to the `.c1h` file, and the calibrated object data are written to the `.c2h` file. The final data quality values are written to the `.cqh` file.

***AIS_CORR:*** This step is functionally no different than FLX_CORR except for the way in which absolute flux is calibrated. The absolute flux calibration is based on data from all apertures and averaged, or normalized, to an arbitrary reference aperture, using the inverse sensitivity information from the AISHFILE reference file. The APR_CORR step must be performed in order for AIS_CORR to have any meaning.

For both methods, points where the inverse sensitivity is zero (i.e., not defined) are flagged with a data quality value of 200. The calibrated spectral data are written to the `.c1h` file, and the calibrated object data are written to the `.c2h` file. The final data quality values are written to the `.cqh` file.

This is the final step of processing for ACCUM mode observations.

## Time Correction (TIM_CORR)

This step corrects the absolute flux for variations in sensitivity of the instrument over time. The correction factor is a function of time and wavelength. The factor is calculated by linear interpolation for the observations' time and wavelength coverage. Then the factor is divided into the object absolute flux. The coefficients are found in table CCSD.

## Special Mode Processing (MOD_CORR)

Data acquired in the rapid-readout, time-resolved, or spectropolarimetry modes receive specialized processing in this step. All data resulting from this additional processing are stored in the `.c3h` file. See "Science Data Acquisition" on page 206 for details of how the output data are stored.

***RAPID Mode:*** For the RAPID mode, the total flux, integrated over all pixels, for each readout is computed. The sum of the statistical errors in quadrature for each frame is also propagated. The following equations are used in the computation.

$$sum(F) = \left(\sum_{x=1}^{NDAT} f(x,F)\right)\left(\frac{NDAT}{good}\right)$$

$$errsum(F) = \sqrt{\left(\sum_{x=1}^{NDAT} ef^2(x,F)\right) \times \left(\frac{NDAT}{good}\right)}$$

Where:

- *f(x,F)* – is the flux in pixel *x* and readout *F*.
- *ef(x,F)* – is the associated error in the flux for pixel *x* and readout *F*.
- *sum(F)* – is the total flux for readout *F*.
- *errsum(F)* – is the associated error in the total flux for the readout *F*.
- *NDAT* – is the total number of pixels in the readout *F*.

- *good* – is total number of good pixels, i.e., pixels with data quality less than 200.

The output `.c3h` file contains two data groups, where the number of pixels in each group is equal to the number of original data frames. Group 1 contains the total flux for each frame, where pixel 1 is the sum for frame 1, pixel 2 the sum for frame 2, etc. Group 2 of the `.c3h` file contains the corresponding propagated errors.

***PERIOD Mode:*** For the PERIOD mode, the pixel-by-pixel average of all slices (NSLICES separate memory locations) and the differences from the average for each slice of the last frame are computed. The following equations are used in the computation:

$$average(x) = \left( \frac{\sum_{L=1}^{NSLICES} f(x, L)}{good(x)} \right)$$

$$errave(x) = \frac{\sqrt{\left( \sum_{L=0}^{NSLICES-1} (ef(x, l))^2 \right)}}{good(x)}$$

$$diff(x, L) = f(x, L) - average(x)$$

$$errdiff(x, L) = \sqrt{(ef(x, L)^2 + errave(x)^2)}$$

Where

- NSLICES – is the number of slices.
- *f(x,L)* – is the flux in slice *L* at pixel *x*.
- *ef(x,L)* – is the error associated with the flux in slice *L* at pixel *x*.
- *average(x)* – is the average flux of all slices at the pixel *x*.
- *errave(x)* – is the error associated with the average flux at pixel *x*.
- *good(x)* – is the total number of good values, i.e., data quality <200, accumulated at pixel *x*.
- *diff(x,L)* – is the flux difference at pixel *x* between slice *L* and the average.
- *errdiff(x,L)* – is the error associated with the flux difference.

The first two data groups of the output `.c3h` file contain the average flux and the associated errors, respectively. Each subsequent pair of data groups contains the difference from the average and the corresponding total error for each slice.

***POLARIMETRY Mode:*** For the POLARIMETRY mode, the data from individual waveplate positions are combined to calculate the Stokes I, Q, U, and V parameters, as well as the linear and circular polarizations and polarization position angle spectra (for details of calculating the Stokes parameters see *FOS*

*Instrument Science Report* 078). Four sets of Stokes parameter and polarization spectra are computed. The first two sets are for each of the separate pass directions, the third for the combined pass direction data, and the fourth for the combined data corrected for interference and instrumental orientation.

## Scattered Light Correction

Scattered light observed in FOS data is produced by the diffraction patterns of the FOS gratings, the entrance apertures, and the micro-roughness of the gratings (extensive work discussed in *FOS Instrument Science Report* 114). A routine pipeline calibration correction is applied only for those gratings that have regions of zero sensitivity to dispersed light (Table 14.6). The values listed in the table apply to spectra with FCHNL=0, NCHNLS=512, NXSTEPS=4, and OVERSCAN=5, i.e., the default FOS observing mode. The correction applied in this way is only a wavelength independent first-order approximation. For details of the correction please see *FOS Instrument Science Report* 103. Note that the scattered light correction is in addition to the background subtraction.

**Table 14.6:** Regions Used for Scattered Light Subtraction

| Detector | Grating | Minimum Pixel Number | Maximum Pixel Number | Total Pixels |
|---|---|---|---|---|
| Blue | G130H | 31 | 130 | 100 |
| Blue | G160L | 901 | 1200 | 300 |
| Blue | Prism | 1861 | 2060 | 200 |
| Red | G190H | 2041 | 2060 | 20 |
| Red | G780H | 11 | 150 | 140 |
| Red | G160L | 601 | 900 | 300 |
| Red | G650L | 1101 | 1200 | 100 |
| Red | Prism | 1 | 900 | 900 |

Since the scattered light characteristics of the FOS are now well understood, a scattered light model is available at STScI. It will be made available shortly for use as a post-observation parametric analysis tool (**bspec**) in STSDAS to estimate the amount of scattered light affecting a given observation. The program was developed by M. Rosa (ESO, ST-ECF)[2]. The amount of scattered light depends on the spectral energy distribution across the whole detector wavelength range of the object being observed and on the sensitivity of the detector. For cool objects the number of scattered light photons can dominate the dispersed spectrum in the UV. Thus, in order to model the scattered light in the FOS appropriately, the red part of the source spectrum has to be known.

2. *FOS Instrument Science Report* 127.

# Post-Calibration Output Files

Several types of calibrated output files are produced by **calfos**. These are listed in Table 14.7. More extensive descriptions of each type of file are provided below.

**Table 14.7:** Output Calibrated FOS Data Files

| Filename Extension | File Contents |
|---|---|
| `.c0h` and `.c0d` | Calibrated wavelengths |
| `.c1h` and `.c1d` | Calibrated fluxes |
| `.cqh` and `.cqd` | Calibrated data quality |
| `.c2h` and `.c2d` | Calibrated statistical error |
| `.c3h` and `.c3d` | Special mode data |
| `.c4h` and `.c4d` | Count rate object and sky spectra |
| `.c5h` and `.c5d` | Flatfielded object count rate spectrum |
| `.c6h` and `.c6d` | Flatfielded sky count rate spectrum |
| `.c7h` and `.c7d` | Background count rate spectrum |
| `.c8h` and `.c8d` | Flatfielded and sky subtracted object count rate spectrum |

The calibrated output files listed in Table 14.7 include:

- **Calibrated wavelength files:** These files contain single-precision floating point calibrated vacuum wavelengths corresponding to the center of each pixel of the science data. The files are identified by the extensions `.c0h` and `.c0d`.
- **Calibrated flux files:** These files contain single-precision floating point calibrated fluxes corresponding to each pixel of the science data. The files are identified by the extensions `.c1h` and `.c1d`.
- **Calibrated data quality files:** The quality flags in these files flag the bad pixel values in the calibrated files. The quality flags from the raw data are updated and additional flags are added for problems detected in the calibration process. The data quality flags are defined in Table 17.3 on page 288. The data quality files are identified by extensions `.cqh` and `.cqd`.
- **Calibrated statistical error files:** These files contain the statistical errors of the original data values. Further, these files are calibrated in lock-step with the science data files. *Errors caused by sky and background subtraction, flatfields, and inverse sensitivity files are not calculated and updated.* The error files are identified by extensions `.c2h` and `.c2d`.
- **Special mode data files:** Data acquired in the rapid-readout, time-resolved, or spectropolarimetry modes require processing steps in addition to (or complementing) those used for standard ACCUM data. The calibrated data

are then stored in special mode data files. For the RAPID mode, the files contain the total flux, integrated over all pixels, and the associated statistical error for each readout. For the TIME RESOLVED mode, the files contain the pixel-by-pixel average of all slices or bins, the difference between each slice or bin and the average, and the average propagated statistical errors. For the POLARIMETRY mode, the file contains the Stokes I, Q, U, and V parameters, the linear and circular polarization, and the polarization position angle. The polarimetric quantities and the propagated errors are calculated for each of the separate pass directions, the combined pass direction data, and the combined pass direction corrected for interference and instrumental orientation (see below). The special mode data files are identified by the extensions `.c3h` and `.c3d`.

- **Intermediate calibrated output files:** At most, six sets of intermediate calibrated output files are produced depending on the observation mode. The files containing the count rate spectra are corrected for undersampling caused by disabled diodes, overscanning, and noise rejection. These files are identified by the extensions `.c4h` and `.c4d`. The flatfielded object spectrum files are identified by the extensions `.c5h` and `.c5d`. The flatfielded sky spectrum files are produced only if a sky observation was obtained. These files are identified by the extensions `.c6h` and `.c6d`. The background spectrum is identified by the extensions `.c7h` and `.c7d`. If the sky is observed, then a smoothed-sky subtracted object spectrum prior to flux calibration is produced. The files containing the smoothed-sky subtracted object spectrum are identified by the extensions `.c8h` and `.c8d`.

If the reference files and reference tables used in the pipeline processing do not reflect the actual instrument performance, calibration errors can occur, leading to artificial features in the calibrated science data. In "FOS Error Sources" on page 251, we list some prominent examples for such errors.

# Polarimetric Calibration

The group contents of the raw (`.d0h`) data file are shown in Table 14.8. Note that the number of pixels in each group is twice the number of pixels in a single spectrum as there are two spectra appended together, one for each pass direction. Once again the number of pixels in the spectrum depends on the values of NXSTEPS and OVERSCAN used (see ACCUM mode for details).

The organization of calibrated polarimetry data files differs from the raw data files and calibrated data taken in other observing modes in that the two pass direction spectra from each readout are stored in separate data groups instead of being concatenated within one group. The wavelength arrays for the different POLSCAN positions should be identical (rotating the waveplate does not change the wavelengths), but the wavelengths are offset by a constant amount between the two pass directions. The calibrated fluxes, the corresponding statistical errors, and the data quality are stored in 2 x POLSCAN number of groups, similar to the wavelengths. Note that for polarimetry data the statistical errors cannot be combined simply. The errors in the Stokes parameters are calculated separately by the data reduction pipeline. The polarimetry-specific data are stored once again as groups in a separate file.[3]

**Table 14.8:** Group Contents of Raw Polarimetry Science Data Files

| Group # | Contents |
|---|---|
| 1 | Polscan 1: pass direction 1 and pass direction 2 |
| 2 | Polscan 2: pass direction 1 and pass direction 2 |
| 3 | Polscan 3: pass direction 1 and pass direction 2 |
| ... | .... |
| 15 | Polscan 15: pass direction 1 and pass direction 2 |
| 16 | Polscan 16: pass direction 1 and pass direction 2 |

The `.c0h` file is a dataset with 2 x POLSCAN groups with wavelengths for both pass directions through the Wollaston prism and each POLSCAN position. Note that the wavelengths for the different POLSCAN positions should be identical, as mentioned earlier, but the wavelengths are offset between the two pass directions by a constant amount.

The `.c1h` file is a dataset with 2 x POLSCAN groups containing calibrated flux for both pass directions and each POLSCAN position. The calibrated fluxes are stored in exactly the same way as the wavelengths. Note that unlike calibrated flux data for non-polarimetric observations, the first group will not represent the absolute flux for the source, but only half, since the light was split into 2 spectra by the polarizer. Representative fluxes are formed by averaging the fluxes from the complete set of POLSCAN positions for each pass direction separately, and then summing the two. Since there is a wavelength shift between the spectra from the two pass directions, to combine the two mean spectra from both pass directions one spectrum must be shifted in wavelength to match the other. *Pass direction 2 is shifted onto pass direction 1. In the summed spectrum, any pixel that has contributions from only one pass direction is set to zero.* The total flux (Stokes I) is computed by the special mode processing phase of **calfos** and is stored in the `.c3h` dataset (see below) and so is more conveniently obtained from there.

The `.c2h` file is a dataset with 2 x POLSCAN groups with the statistical error of the calibrated flux for both pass directions and each POLSCAN position. The flux errors are stored in exactly the same way as the wavelengths and fluxes. As for the calibrated flux dataset, this dataset differs from the statistical errors for non-polarimetric data and the errors cannot be simply combined. We suggest that the error on the Stokes I parameter computed by the polarimetry processing be used as the total flux error.

The `.cqh` file is a dataset with 2 x POLSCAN groups with the data quality values for the calibrated fluxes. The organization is exactly the same as that of the calibrated fluxes dataset.

3. See *FOS Instrument Science Report* 078.

The group organization of the `.c0h`, `.c1h`, `.c2h`, and `.cqh` files is shown in Table 14.9.

**Table 14.9:** Group Organization of the Calibrated .c0h, .c1h, .c2h, and .cqh Files

| Group | Contents Depending on Calibration File |
|---|---|
| 1 | Polscan 1, Pass direction 1: wavelength, flux, error or data quality |
| 2 | Polscan 1, Pass direction 2: wavelength, flux, error or data quality |
| 3 | Polscan 2, Pass direction 1: wavelength, flux, error or data quality |
| 4 | Polscan 2, Pass direction 2: wavelength, flux, error or data quality |
| ... | ... |
| 31 | Polscan 16, Pass direction 1: wavelength, flux, error or data quality |
| 32 | Polscan 16, Pass direction 2: wavelength, flux, error or data quality |

The `.c3h` file is a dataset with 56 groups containing the reduced polarimetry data. The dataset is organized into four sets of 14 groups, where groups 1 through 14 contain the Stokes parameter and polarimetry data for pass direction 1, groups 15 through 28 for pass direction 2, groups 29 through 42 contain the merged data from both pass directions 1 and 2, and groups 43 through 56 contain the merged data corrected for interference and instrument orientation. The organization of the `.c3h` file is shown in Table 14.10.

Note that the wavelengths corresponding to the first set of 14 groups are given by the wavelength array for the first pass direction (i.e., group 1 of the `.c0h` file), while for the second set of 14 groups (groups 15 through 28) the corresponding wavelengths are given by the wavelength array for the second pass direction (i.e., group 2 of the `.c0h` file). For the merged data in the third and fourth sets of 14 groups (groups 29 through 56), the corresponding wavelengths are given by the first pass direction.

**Table 14.10:** Group Organization of the Calibrated .c3h File

| Group # Pass Direction 1 | Group # Pass Direction 2 | Group # Pass Direction 1&2 | Group # Pass Direction 1&2 corrected | Contents |
|---|---|---|---|---|
| 1 | 15 | 29 | 43 | Stokes I |
| 2 | 16 | 30 | 44 | Stokes Q |
| 3 | 17 | 31 | 45 | Stokes U |
| 4 | 18 | 32 | 46 | Stokes V |
| 5 | 19 | 33 | 47 | Stokes I error |
| 6 | 20 | 34 | 48 | Stokes Q error |
| 7 | 21 | 35 | 49 | Stokes U error |
| 8 | 22 | 36 | 50 | Stokes V error |
| 9 | 23 | 37 | 51 | Linear polarization |
| 10 | 24 | 38 | 52 | Circular polarization |
| 11 | 25 | 39 | 53 | Polarization position angle |
| 12 | 26 | 40 | 54 | Linear polarization error |
| 13 | 27 | 41 | 55 | Circular polarization error |
| 14 | 28 | 42 | 56 | Polarization position angle error |

# CHAPTER 15:
# FOS Error Sources

**In This Chapter...**

Photometric Inaccuracies / 251
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Other Data Problems / 267

Along with other error sources, deviations of target positions from the nominal "best" position can affect the accuracy of both the photometric and wavelength calibration. These deviations can occur in two dimensions. In the case of a simultaneous deviation in both the x- and y-direction, both photometric and wavelength accuracies are affected. In the following sections, we separately examine the deviations along and perpendicular to the dispersion direction.

## Photometric Inaccuracies

Below we describe briefly each of the sources of photometric errors:

- Time-dependent variations in FOS sensitivity.
- Target miscentering.
- Flatfields.
- Change in telescope focus.
- Location of spectra.
- Thermal breathing.
- Jitter.
- GIM.
- Calibration system offsets.

## Time-Dependent Variations in FOS Sensitivity

FOS sensitivities have occasionally displayed time-dependent variations. None of these variations have ever been accounted for in routine pipeline processing. However, all can be accounted for by re-processing the data with the new AIS_CORR flux calibration method and the most recent reference files and tables.

From early 1991 through mid-1992 the FOS experienced a systematic decline in sensitivity for all gratings and detector combinations. The systematic degradation in sensitivity of the FOS until mid 1992 was about 10% per year for all gratings on the blue side, and approximately 5% (except for the G190H grating) per year for the red side. The degradation in the G190H and G270H grating and the red detector was ~10% per year and was wavelength dependent.[1] The pre-COSTAR degradation leveled off between mid-1992 and the end of 1993. In Figure 15.1 we show the time dependence of the pre-COSTAR FOS sensitivity in a typical FOS/BL grating. Pre-COSTAR sensitivity changes for a typical FOS/RD grating are shown in Figure 15.2 and for the FOS/RD G190H in Figure 15.4. Post-COSTAR sensitivity shows a dip relative to pre-COSTAR values between approximately 1500 and 2500 Å. Except for FOS/RD G190H and G160L post-COSTAR sensitivity has shown no temporal variation. From February, 1994 through July, 1994 FOS/RD G190H sensitivity dropped by approximately 2% and then increased from 3 to 8% between July, 1994 and July, 1995. FOS/RD G160L showed similar changes shortward of 2200 Å. Figures 15.4 and 15.7 show the time dependence of post-COSTAR FOS sensitivity for the FOS/RD G190H grating.

Archived FOS observations should always be re-processed with the AIS_CORR flux calibration method using the most recent set of reference files and tables.

1. *FOS Instrument Science Report* 077.

**Figure 15.1:** Pre-COSTAR Typical Time Dependence on BLUE Side

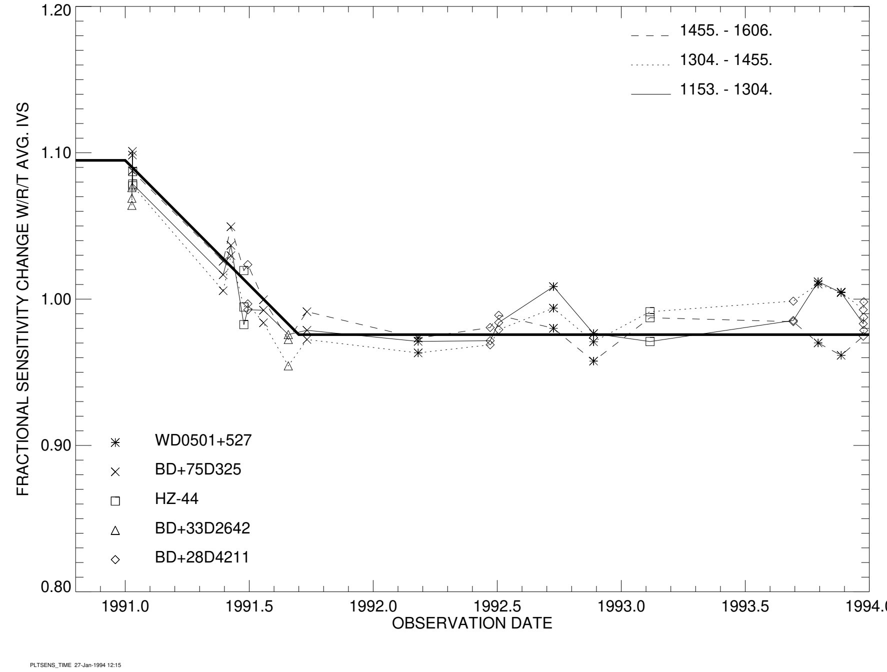



**Figure 15.2:** Pre-COSTAR Typical Time Dependence on RED Side

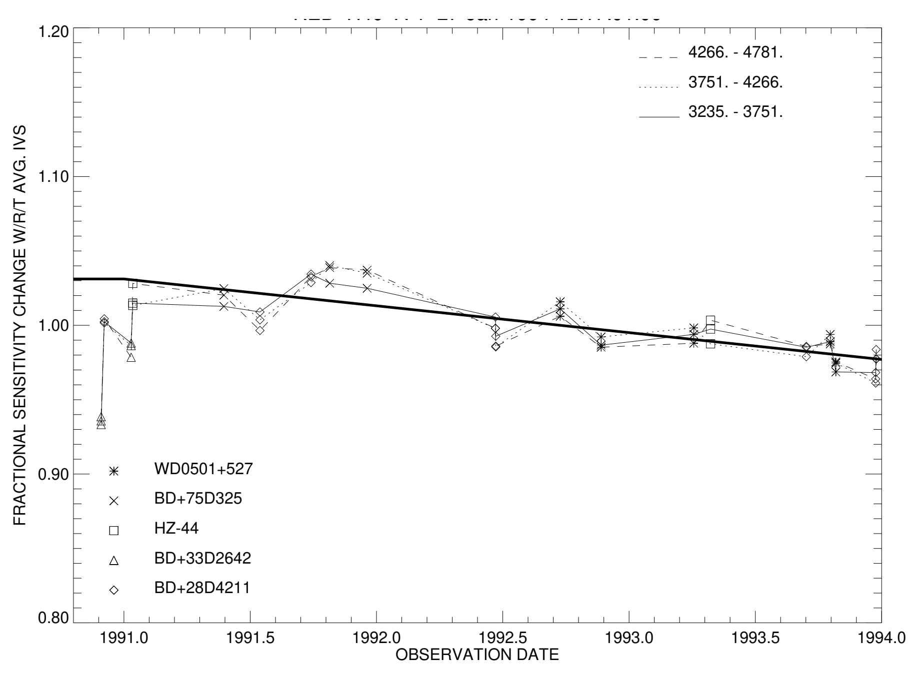


**Figure 15.3:** Post-COSTAR Changes in Sensitivity Over Time

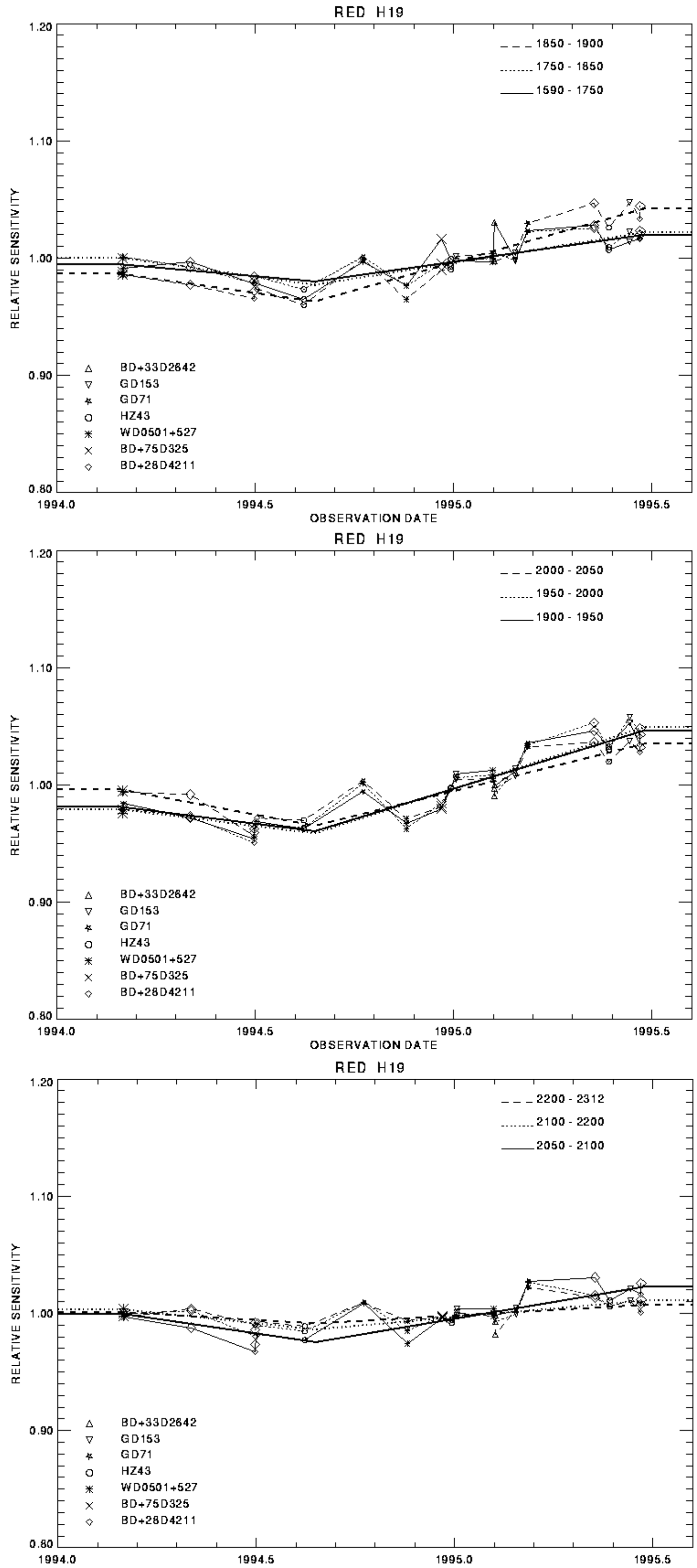


**Figure 15.4:** Pre-COSTAR Time Dependence in G190H Grating on RED Side

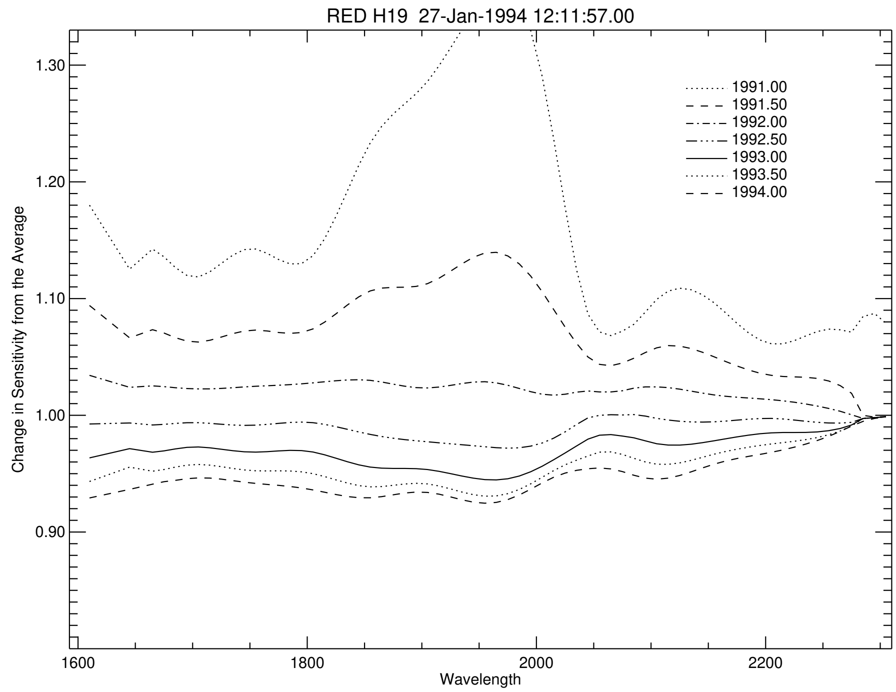
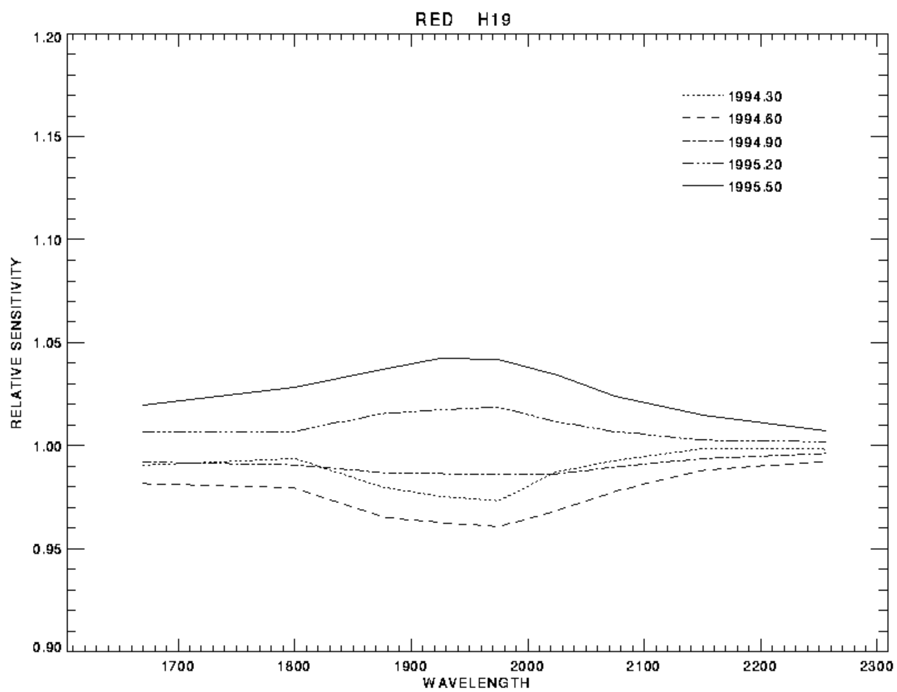



**Figure 15.5:** Corrections as a Function of Wavelength for H19



## Target Miscentering

Inaccurate centering of a target in the aperture also leads to photometric errors because of loss of signal. The flux from the source will be underestimated systematically. Miscentering is likely to be the dominant error affecting flux calibration for small aperture observations. One can estimate the photometric error due to miscentering of the target in the aperture from the information supplied in Figure 15.6 and Table 15.1. Figures 15.6 a and b show, for the circular 1˝ aperture, the post-COSTAR diminution of the transmitted flux from a point source versus the pointing error (miscentering). Table 15.1 gives the maximum pointing errors for different types of target acquisitions. Thus, for example, for observations which used a binary acquisition and were taken through the 1˝ circular aperture, <3% of the flux will be lost, while for observations using a five stage peak-up acquisition but taken through the 0.3˝ aperture, about 3 to 5% of the flux will be lost for a point source. Analysis of several peak-up acquisition observations shows that the fall-off in the signal is gradual except when the target is within about 0.1” of the edge of the aperture. The light loss is ~50% when the target lies on the aperture edge.

**Figure 15.6:** Post-COSTAR Transmitted Flux Versus Pointing Error for the Single 1.o˝ Aperture

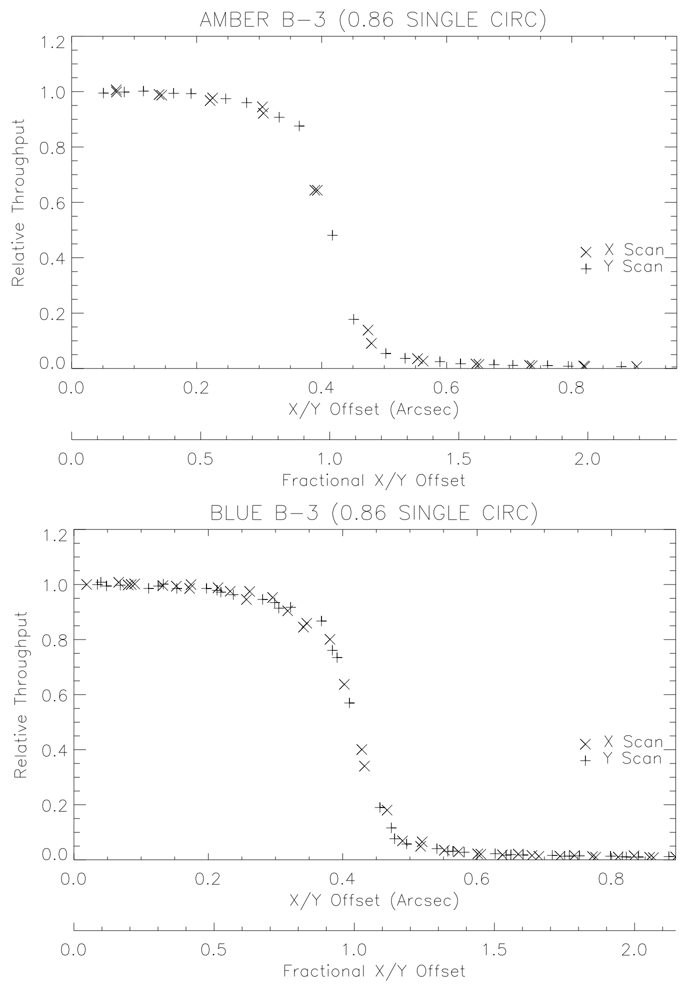


**Table 15.1:** Target Acquisition Pattern Pointing Accuracies and Overhead

| Aperture | Pattern Name | Search-size-X | Search-size-Y | Step-size-X (arcsec) | Step-size-Y (arcsec) | Pointing Accuracy (arcsec) | Overhead (minutes) |
|---|---|---|---|---|---|---|---|
| 4.3 | A | 1 | 3 | - | 1.23 | - | 7 |
| 1.0 | B1 | 6 | 2 | 0.61 | 0.61 | 0.43 | 12 |
| 0.5 | C1 | 3 | 3 | 0.29 | 0.29 | 0.21 | 10 |
| 0.3 | D1 | 5 | 5 | 0.17 | 0.17 | 0.12 | 17 |
| | D2 | 5 | 5 | 0.11 | 0.11 | 0.08 | 17 |
| | D3 | 5 | 5 | 0.052 | 0.052 | 0.04 | 17 |
| | E1 | 4 | 4 | 0.17 | 0.17 | 0.12 | 14 |
| | E2 | 4 | 4 | 0.11 | 0.11 | 0.08 | 14 |
| | E3 | 4 | 4 | 0.052 | 0.052 | 0.04 | 14 |
| | F1 | 3 | 3 | 0.17 | 0.17 | 0.12 | 10 |
| | F2 | 3 | 3 | 0.11 | 0.11 | 0.08 | 10 |
| 1.0-PAIR | B2 | 6 | 2 | 0.61 | 0.61 | 0.43 | 12 |
| 0.5-PAIR | C2 | 3 | 3 | 0.29 | 0.29 | 0.21 | 10 |
| 0.25-PAIR | P1 | 5 | 5 | 0.17 | 0.17 | 0.12 | 17 |
| | P2 | 5 | 5 | 0.11 | 0.11 | 0.08 | 17 |
| | P3 | 5 | 5 | 0.052 | 0.052 | 0.04 | 17 |
| | P4 | 4 | 4 | 0.11 | 0.11 | 0.08 | 14 |
| 2.0-BAR | BD1 | 1 | 11 | - | 0.052 | 0.03 | 11 |
| 0.7-BAR | BD2 | 1 | 11 | - | 0.052 | 0.03 | 11 |
| SLIT | S | 9 | 1 | 0.057 | - | 0.03 | 10 |
| ACQ/BIN RED | Z | - | - | - | - | 0.12 (1-σ) | 9 |
| ACQ/BIN BLUE | Z | - | - | - | - | 0.08 (1-σ) | 9 |

## Flatfield Correction

FOS flatfields are prepared from precisely pointed (≤0.04” pointing accuracy), high S/N observations (S/N ≥ 200 per pixel, typically) of two relatively featureless spectrophotometric stars, BD+28D4211 and G191-B2B (also known as WD0501+527). All FOS flatfield reference files are actually unity-normalized inverse flatfields, that are applied as multiplicative operators in the **calfos** pipeline data reduction. The overall flatfield correction generally has an accuracy of better than 3%. However, flats for certain specific dispersers, apertures, and spectral regions can be somewhat poorer. Recent studies (Keyes, *2nd HST Calibration Workshop*, 1995) have shown that substantial (5 to 15%) flatfield variation occurs on spatial size-scales as small as 0.2" for all detector and disperser combinations, so that precise flatfield correction is only possible for science targets acquired with the same high pointing accuracy used for calibration observations. So-called *superflats* provide the best quality flatfields.[2]

The FOS/RD G190H flatfields have displayed time dependence and substantial spatial dependence in both pre- and post-COSTAR periods. All pre-COSTAR flatfields are somewhat aperture dependent. However, individual aperture-specific flatfield observations were not made for many apertures in the pre-COSTAR period. Little post-COSTAR aperture dependence exists between individual single apertures or individual paired apertures. Due to the substantial photocathode granularity spatial variations, flatfield reference files derived from single aperture observations should never be used to correct paired aperture observations and vice versa.

The following general recommendations summarize the guidelines for the applicability of FOS flatfield reference files.

### Pre-COSTAR

***FOS/BL:***

- For all FOS observations *before* January 1, 1992, with the SINGLE aperture and BLUE detector use the science verification (SV) 1.0″ aperture flats.
- For observations *after* January 1 1992 use the new 4.3″ aperture flats (superflats).
- The BLUE side data taken in a paired aperture during 1991 should be corrected with the new 4.3″ aperture flats computed for the UPPER and LOWER aperture positions or should be left uncorrected.
- In no circumstances should the SV 1.0″ SINGLE aperture flats be used to correct data taken in a paired aperture.

***FOS/RD:***

- For the G190H, G270H, and G160L dispersers, the Cycle 3 superflats of Lindler et al.[3] should be used for all observations obtained after August 7, 1993.
- For G400H, G570H, G650L, and the PRISM, the Cycle 3 superflats of Lindler et al. should be used for all observations obtained after 18 June, 1992.
- For all other FOS/RD observations with the above dispersers, the FOS/RD flatfield obtained closest to the observation date should be used.
- No SINGLE aperture flats should be used to correct data obtained with a paired aperture.

---

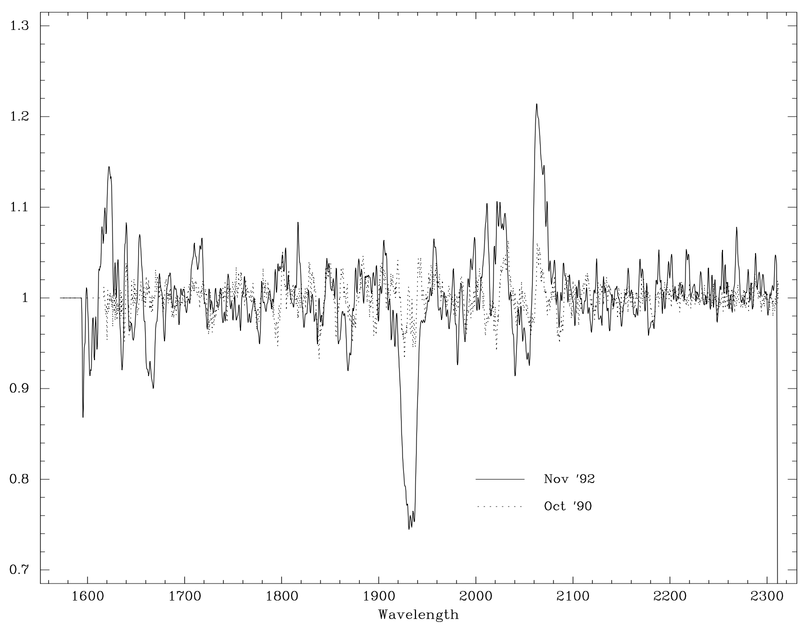
2. The superflat observational and analysis procedures are explained in detail in *FOS Instrument Science Report* 088.

3. *FOS Instrument Science Report* 134.

- For G780H, no pre-COSTAR flatfields exist—unity correction is applied in the pipeline.
- For all barred apertures, no pre-COSTAR flatfields exist —unity correction is applied in the pipeline.

The FOS/RD flats (especially G190H, G160L, and to a lesser extent G270H) show significant wavelength structure (Figure 15.7). These flats also showed strong (>10%) wavelength-dependent temporal variations during the first year of HST operation when flatfields were not routinely monitored. Between January 1992 and June 1992, the G190H, G160L, and G270H FOS/RD flatfields were monitored monthly. During this intensive monitoring period the flats varied by less than 2%. For the duration of the pre-COSTAR period, and indeed post-servicing, these flats have been monitored about every 3 months. Several substantial (≥5%) new features appeared between June and November 1992. For the remainder of the pre-COSTAR era (ending December 1993) changes were less than 2%.

**Figure 15.7:** Red G190H Flatfield Reference Files




The StarView Calibration screens will almost always return the current recommended best flatfield reference file to use on your dataset.

### *Post-COSTAR*

For both detectors:

- For all single aperture observations apply 4.3″ aperture superflat-derived flatfield with appropriate USEAFTER date.

- All Cycle 4 SINGLE aperture high-dispersion observations obtained prior to July 13, 1994 should be recalibrated with current reference files as pre-COSTAR flatfields were used for these combinations prior to this date.
- All Cycle 4 SINGLE aperture low-dispersion observations obtained before July 1, 1995 should be re-calibrated with the current reference files as pre-COSTAR flatfields may have been used for these combinations prior to this date.
- All Cycle 4 PAIR aperture observations should be re-calibrated with new reference files to be delivered fall, 1995 (please check the FOS world wide web page, especially the “Documentation” section, for updates). Unity flats (no correction) have been applied to all post-COSTAR paired observations through September, 1995.
- SINGLE aperture flats for apertures smaller than 4.3” also will be available in fall, 1995. Nonetheless, little aperture dependence is seen in post-COSTAR single aperture flatfields. Please consult the FOS Reference File Reference Guide on STEIS for availability and applicability.
- Again, as for pre-COSTAR data, no SINGLE aperture flats should be used to correct data obtained with a paired aperture.
- For all barred apertures, no post-COSTAR flatfields exist - unity correction is applied in the pipeline.

A very strong photocathode blemish exists in FOS/BL G160L SINGLE aperture spectra. The contribution of the feature is extremely sensitive to target centering, such that large (often >20%) uncertainties exist in the flatfield calibration of the spectral region between 1500 and 1560 Å. Modest post-COSTAR time-variation of FOS/RD G190H flatfields has been observed. Between November 1994 and February 1995, 2 to 4% changes occurred in the same spectral regions that were active in the pre-COSTAR era.

In order to assess the impact of the flatfield used in the data reduction process for any particular FOS observations, the target spectrum should be compared with standard star spectra and with similar science observations taken as nearly contemporaneously as possible. Further, the flatfield used in the calibration of the target spectrum should be compared with any other available flats for that instrumental configuration.[4] Figures 15.8 and 15.9 show representative flatfields for high dispersion gratings for both FOS detectors.

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4. Detailed information about flatfields is provided in *FOS Instrument Science Reports* 075, 078, 088, 090, 134, and 143. Updates will be posted on STEIS.

**Figure 15.8:** Typical Flatfield Reference Files for Blue (FOS/BL) High Dispersion Gratings

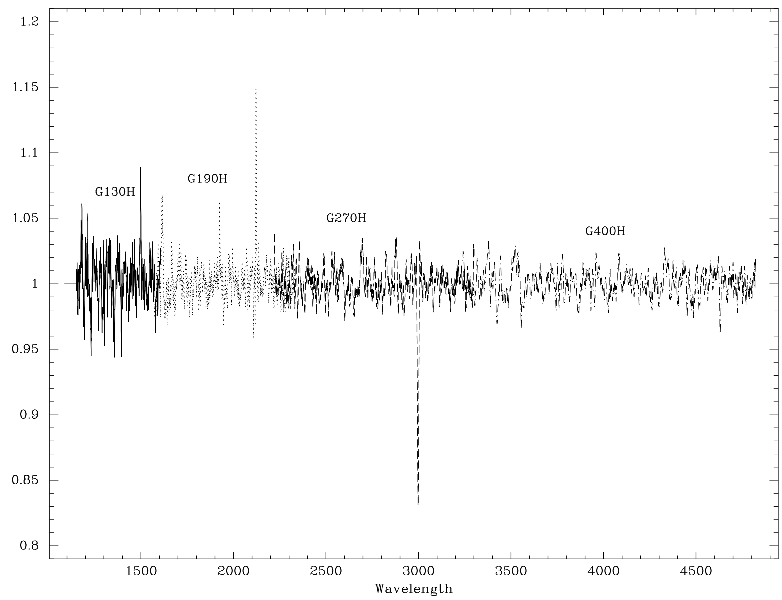
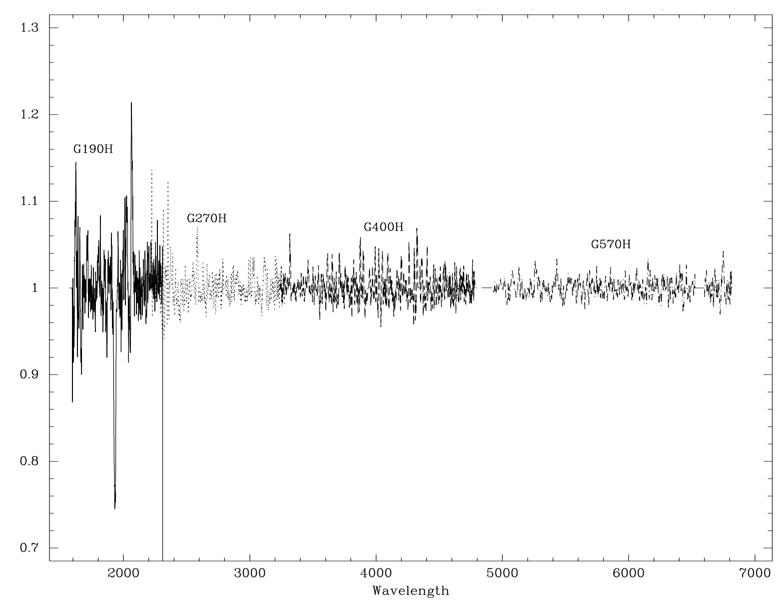



**Figure 15.9:** Typical FlafField Reference Files for Red (FOS/RD) High Dispersion Gratings




## Change in Telescope Focus

Systematic variations of pre-COSTAR FOS sensitivity occurred because OTA focus adjustments did not occur with sufficient frequency to keep up with the shrinkage of the graphite epoxy structure that is caused by outgassing on orbit.[5] A change in focus by 15 microns led to photometric changes of up to 8% in the 4.3” aperture. The photometric variations also depend on aperture and very slightly on wavelength. All such variations are accounted for in the new calibration method (APR_CORR, AIS_CORR, and TIM_CORR). Focus changes have been monitored very closely since the installation of COSTAR, and no significant focus-related sensitivity variations have occurred.

## Location of Spectra (Y-bases)

The ability to acquire FOS spectra depends on knowledge of where the spectra lie on the photocathode because electrons from a region of the photocathode the size of the diode array are deflected onto the diode array without magnification. Pre-COSTAR calibration data to determine the y location (perpendicular to the dispersion direction) of the spectra on the photocathode have shown that there is a trend with time in the y location of spectra for all gratings on the blue side. These trends are not seen on the red side.[6] Furthermore, the shapes of the spectra on the photocathode are not linear, but have a curvature of +/– 20 y-base units because of small distortions in the magnetic fields of the Digicon detectors.

Recent analyses of post-COSTAR data show that the trend of a spatial drift with time in the positions of the spectra for all gratings observed with the blue (FOS/BL) detector continues, while the locations of the spectra for all gratings and the red (FOS/RD) detector are still scattered randomly.[7] The amount of scatter in the mean y-base location has increased since on-board GIM correction started and the routine DEPERM (clearing of the ambient magnetic field in the detector) was turned off. A test has been scheduled to check the effect of DEPERM on the scatter in the YBASES.

The uncertainties in the locations of the spectra have affected both ACQ/BIN pointing accuracy and FOS photometric accuracy. The size of these uncertainties with ACQ/BIN forced us to follow ACQ/BIN with a time-consuming ACQ/PEAK to improve the target centering for science with all the small (smaller than 1.0”) apertures. The photometric quality of the data, especially for FOS/RD and the 1.0” aperture, are compromised due to the large fluctuations in the location of the spectrum. Further, this is not a simple matter of losing light, but the effect is also wavelength dependent. On average, assuming that the locations of the spectra are known to an accuracy of only 20 YBASE units, for the large apertures (≥1.0”) 3% of the light of point sources and up to 20% for extended objects can be lost!

## Thermal Breathing

There is a change in focus due to the *thermal breathing* of the secondary mirror support structures. The change in temperature as the spacecraft crosses the terminator affects the support structure and moves the secondary mirror, which in

5. *FOS Instrument Science Report* 102.

6. *FOS Instrument Science Reports* 096 and 110.

7. *FOS Instrument Science Report* 133.

turn changes the focus. This effect occurs on timescales equal to the orbital period of the spacecraft. The pre-COSTAR photometric error associated with thermal breathing is <4% and affects the flux in a random and uncorrectable way. The post-COSTAR effect is reduced substantially due to the much narrower PSF and typically affects only the 0.3″ and smaller apertures. Only in very long (> 3000 seconds) RAPID mode observations can one see the periodicity (and possibly correct for it).

## Jitter

*Jitter* is mostly due to the thermal instability of the solar panels. The greatest excursions occur when the spacecraft crosses the terminator, lasting for a few minutes. The jitter causes the telescope to mispoint, moving the target in the aperture. This problem has the largest effect on the small apertures (0.3″ and smaller), because the target can move out of the aperture for a short period. The associated photometric errors cannot be accurately determined because the y-location of the spectra is unknown. The photometric error is rarely more than 1%, but always less than 3%.

## Geomagnetically Induced Image Motion

Off-line geomagnetically-induced image motion (GIM) correction is needed only for data taken before April 5, 1993. For spectra taken later, the GIM correction is applied onboard the spacecraft.

An FOS observation requires the electrons from the photocathode to be magnetically deflected onto the diode array. Due to insufficient magnetic shielding of the Digicon detectors, the earth's magnetic field affects where the electrons fall on the diode array. The effective magnetic field experienced by the electrons depends on the location of the spacecraft in the earth's magnetic field. The shift of the spectrum due to the changes in the effective magnetic field is both in the dispersion direction (x) and perpendicular to the dispersion direction (y). As of April 5, 1993, this geomagnetically-induced image motion (GIM) problem has been corrected for in real-time aboard the spacecraft through the application of a spacecraft position-dependent correction to the magnetic deflection to compensate (in both x and y) for the effects of the earth's magnetic field. However, before April 5, 1993, there was no real-time correction for GIM. The effect of the x-shift in the photoelectrons' impact point is to effectively shift the spectrum in the dispersion direction as a function of time. This displacement can be seen in data taken before April 5, 1993, by plotting the individual groups of raw data on a single plot (use the STSDAS **grspec** task) and noting the shift (in x) of the centroids of individual emission or absorption lines. The **calfos** task corrects for the x-shift caused by the GIM (as long as the OFF_CORR switch is set to

"PERFORM") in the creation of the calibrated spectral data (.c0h and .c1h files).[8]

The GIM correction for a given group in an observation is determined from the orbital position of the spacecraft at the mid-point of the observation time for each group. To avoid resampling the data, and hence losing error information, the correction is applied as an integral pixel shift, although the accuracy of the correction is +/– 0.5 pixel where each pixel is 1/4 diode in the standard spectrophotometry modes. However, there is no way to correct for the photometric effects of the shift in y introduced by GIM. The y-shift effectively causes the point spread function (PSF) from the target to move on the diode array, leading to the loss of light off the edge of the array. This creates a time-dependent error in the flux, which is most severe for poorly-centered observations. For well centered observations through the 4.3″ aperture the error will be <5%.

Some data taken after April 5, 1993 may not have had the on-board GIM correction applied. The header keyword YFGIMPEN will tell you if the onboard correction was enabled; if the value is "TRUE" then the onboard correction was applied. The onboard GIM correction is applied on a finer grid than is provided by the pipeline GIM correction in both the x and y axes. In the x direction the onboard GIM correction is applied in units of 1/32 of the width of the diodes, while in the y direction the unit is 1/32 of the diode height. The onboard GIM correction is calculated and updated every 30 seconds.[9]

## Absolute Photometric Calibration System Offsets

All pipeline-processed (FLX_CORR) pre-COSTAR FOS observations have been placed on the absolute photometric system of Bohlin et al. (1990). All post-COSTAR pipeline-processed observations prior to September, 1995 (FLX_CORR) are on an early version of the white dwarf flux scale based upon G191-B2B. AIS_CORR pre- and post-COSTAR observation processing produces fluxes on a slightly revised version of the white dwarf flux scale, based upon eight standard stars[10]. The pre-COSTAR FLX_CORR system differs from the AIS_CORR scale by <15% for wavelengths < 2000 Å, ~5% for the wavelength range 2000–3500 Å and <3% for wavelengths > 3500 Å (see Table 15.2). An illustrative comparison of the pre-COSTAR FLX_CORR flux scale and the white dwarf flux system is shown in Figure 15.10. The difference between the post-COSTAR FLX_CORR system and the recommended AIS_CORR system is typically < 3% for the 4.3″ and 1.0″ apertures and high dispersion gratings, and exceeds 10% only in small regions for the low dispersion modes.

8. Prior to May 1991, **calfos** did not correct for GIM. However, all data in the HST Archive have been reprocessed after the GIM correction was added to **calfos**. Therefore, if you have FOS data that were processed before May 1991, you should retrieve the data from the HST Archive instead of using the data on your tape.

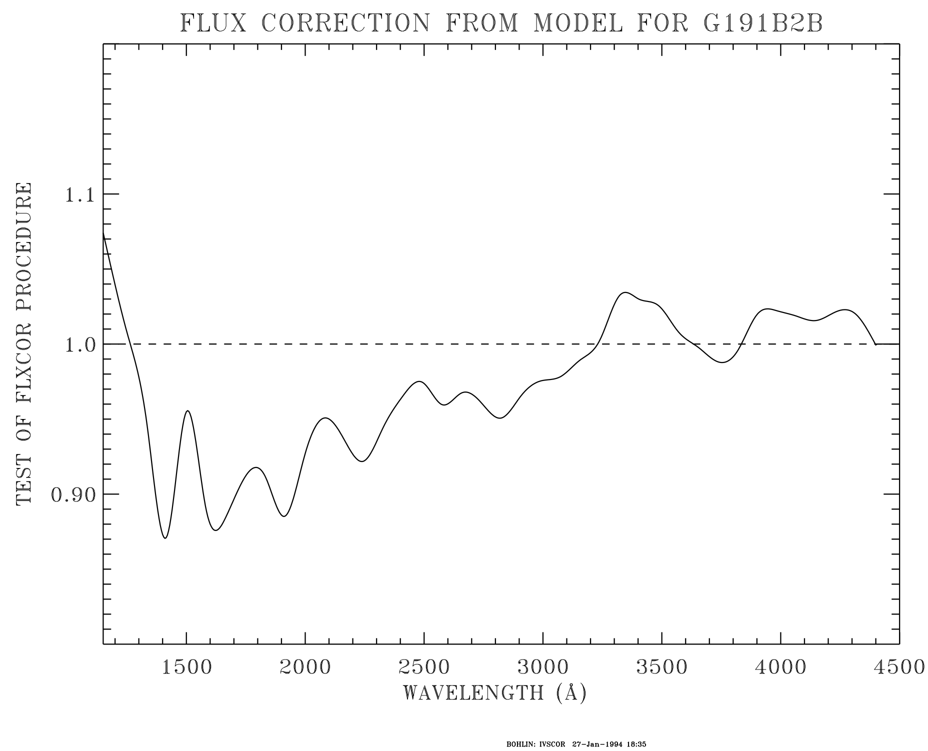
9. *FOS Instrument Science Report* 098.

10. *FOS Instrument Science Report* 144.

**Table 15.2:** Pre and Post-COSTAR Calibration System Differences

| Wavelength | % Uncertainty |
|---|---|
| Far UV | ~10% |
| Near UV | ~5% |
| Visible | ~3% |

**Figure 15.10:** Pre-COSTAR Pipeline Ratio of HST to White Dwarf Flux Scales




# Wavelength Calibration Errors

Of the above calibration error sources the following four affect most severely the accuracy of the wavelength scale:

- Filter-grating wheel (FGW) non-repeatability.
- Aperture wheel non-repeatability.
- Residual uncertainty of the magnetic field after GIM correction.
- Target mis-centering.

## Filter-Grating Wheel Non-Repeatability

Although the positions of the filter-grating wheel (FGW) in the beam of light are stabilized by notches, there is still some mechanical non-repeatability of the wheel position, the x-component of which influences the accuracy of the wavelength calibration. The amplitude of this effect has been measured recently based on post-COSTAR data (Koratkar & Martin 1995, *2nd HST Calibration Workshop*). They find that the 1σ non-repeatability is of the order of 0.1 diodes, with occasional deviations of up to 0.35 diodes.

## Aperture Wheel Non-Repeatability

The non-repeatability of the aperture position introduces an additional uncertainty of the location of spectra along the dispersion direction on the same order of magnitude with a 1σ uncertainty of about 0.1 diodes.[11] Since most observations are taken with only one aperture, this effect often causes an offset for the entire sequence of measurements within one telescope visit on the target(s).

## Residual Uncertainty of Magnetic Field after GIM Correction

We have noted above that the GIM correction cannot be applied in the y-direction. In the x-direction, i.e., in the dispersion direction, it minimizes the effect of the earth's magnetic field on the internal magnetic field. However, a small residual uncertainty is left, which amounts to about 0.03 diodes (1σ) for FOS/RD. On the blue side, this test has been executed twice, first during SMOV (February 1994), and again in June 1995. However, the results are not yet available. It is known from experience with earlier data that the shielding of the blue detector is better than that of the red side, and the residual uncertainties after correction will correspondingly also be lower.

## Target Miscentering

Target miscentering can also lead to photometric inaccuracies due to flux losses when the target is located close to the edge of the aperture. The highest errors can occur when observing with the smallest (0.3” or smaller) apertures. With the 0.3” aperture a target miscentering of 0.12” (as routinely achieved as target centering accuracy with the binary acquisition mode) leads to a flux loss of about 60% with respect to perfect centering. The expected flux loss for a pointing accuracy of 0.04” (as reached with a 4-stage peak-up sequence) leads to flux losses of less than 4% in the 0.3” aperture. Observing with the 1.0” aperture, the same pointing accuracy of 0.04” leads to no measurable flux losses. For this aperture, the pointing accuracy of the binary target acquisition technique is sufficient. It will lead to flux losses of less than 3%

11. See *FOS Instrument Science Report* 131.

# Other Data Problems

In this section we describe how to recognize and correct major problems that might affect your pipeline processed FOS data. The problems addressed here are:

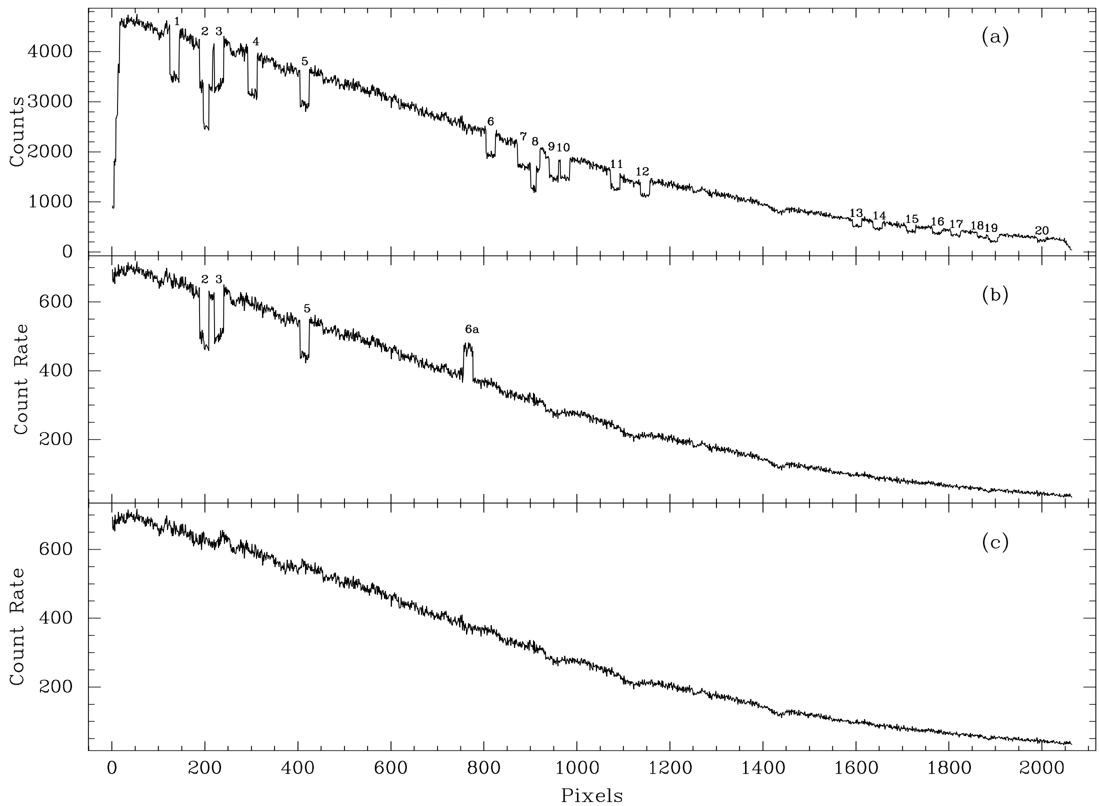
- Effect of an incorrect dead diode reference file.
- Effect of a noisy diode.
- Effect of an incorrect flatfield reference file.
- Under-subtraction of background light.
- Scattered light.

## Effect of Incorrect Dead Diode Reference File

During pipeline processing, **calfos** uses the dead diode reference file (the list of all disabled diodes) to determine how many diodes contributed towards the counts for each pixel. This information is needed to calculate the exposure time per pixel and convert counts to count rates (see page 237). If an incorrect dead diode reference file is used, **calfos** does not have an accurate reporting of the diodes that were used for the onboard integration. This leads to serious errors in the count rates and fluxes for affected pixels. The effect of incorrect dead diode correction (see Figure 15.11) has a very distinct signature, which looks like an *absorption or emission feature* with sharp edges, extending over a fixed number (NXSTEPS x OVERSCAN) of pixels (usually 20). Further, the dead diode absorption feature typically does not go to zero counts because more than one diode contributes towards the counts in a given pixel. Thus the depth of the absorption feature for a pixel affected by a single missed disabled diode is 1 – [(OVERSCAN – 1) / (OVERSCAN)], or usually 20%. In Figure 15.11, panel (a) shows the raw counts and the dead diodes labeled 1-20. Panel (b) shows the count rate data from the pipeline processing from the `.c4h` file. Some of the dead diodes are correctly removed in the pipeline calibration while others are not. This occurred because an incorrect dead diode reference file was used in the processing of the data. Panel (c) shows the `.c4h` file *after* the correct dead diode reference file was used in the calibration.

If you notice a feature in your data similar to the absorption feature described above, you should be suspicious that an incorrect dead diode reference file was used in the pipeline processing of your data. You can use the Calibration Reference screens in StarView to determine whether a more appropriate set of calibration reference files (including the dead diode reference file) now exist to calibrate your data. If so, you can retrieve those files and recalibrate your data using **calfos** (see “Recalibrating FOS Data” on page 277). If there is no change in the recommended dead diode reference file for your data and you are still suspicious that your data are affected by a missed disabled diode, contact the STScI Help Desk (`help@stsci.edu`) for further assistance.

**Figure 15.11:** Effect of Incorrect Dead Diode Correction




## Effect of Noisy Diode

The effect of a noisy (or *hot*) diode is typically an *emission feature* extending over a fixed number (NXSTEPS x OVERSCAN) of pixels (typically 20). Figure 15.12 shows an observation where pixels 400 to 420 are affected by a noisy diode. *This effect cannot be removed by recalibrating the data*; you can manually edit the data to cosmetically smooth over or blank out the affected pixels. IRAF or STSDAS tasks to do this include **fixpix** or **splot** in its *etch-a-sketch* mode.

## Effect of Incorrect Flatfield Reference File

During pipeline calibration, **calfos** corrects for small scale (less than 10 diode) inhomogeneities in the sensitivity of the FOS by multiplying each spectrum by an inverse flatfield. Small scale sensitivity variations result from both small scale inhomogeneities in the photocathode and diode-to-diode sensitivity variations. If an incorrect, or inappropriate, flatfield reference file is used to flatfield the data, small *emission-like* or *absorption-like* features will appear in the spectrum corresponding to sensitivity variations that were introduced or left uncorrected by the flatfielding.

**Figure 15.12:** Effect of Noisy Diodes

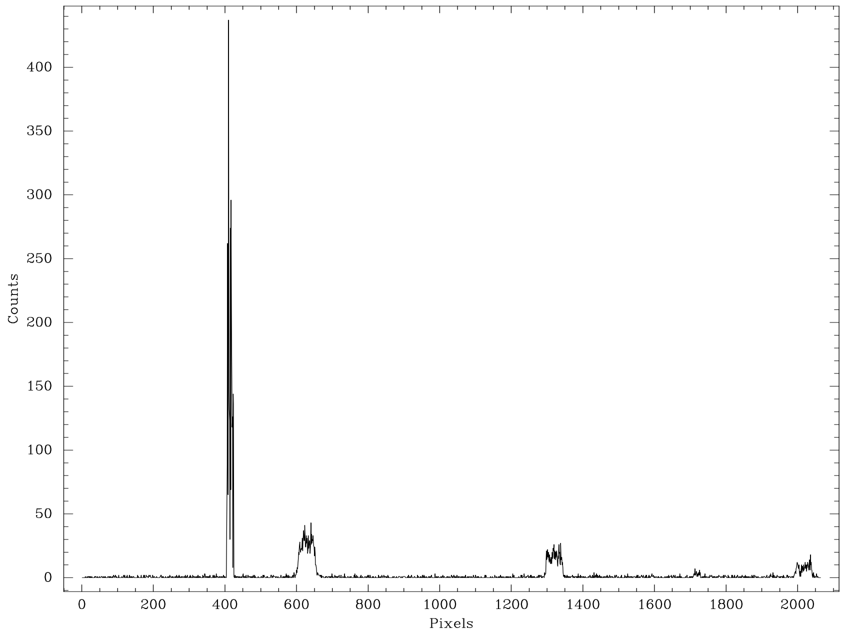
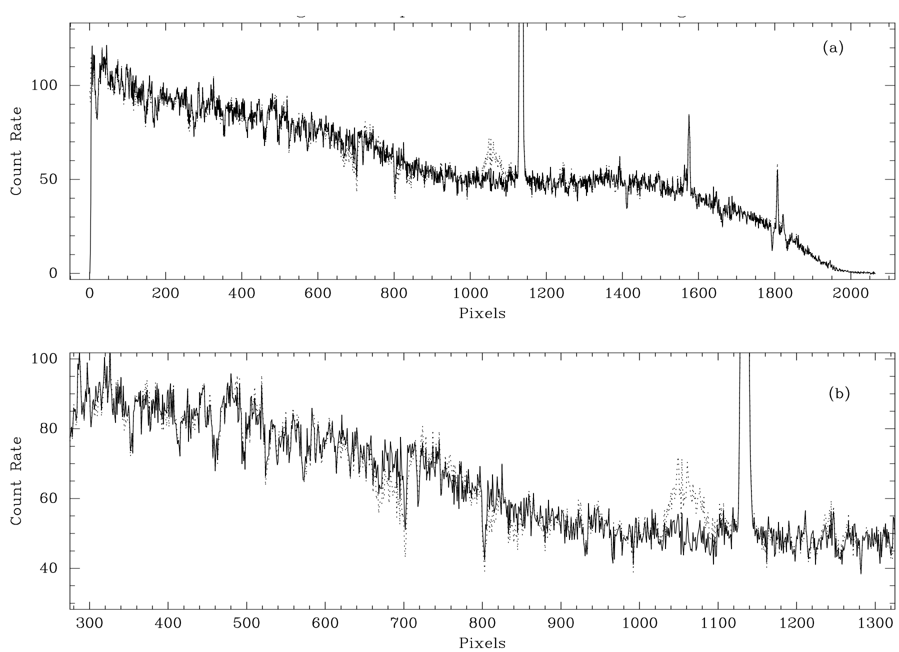



Figure 15.13 shows an example of a spectrum that was flatfielded incorrectly. Panel (a) shows the count rate data in the `.c5h` file that results from using both correct (solid line) and incorrect (dotted line) flatfield files. Panel (b) shows a blowup of the region from 300 to 1300 pixels of the same data.

**Figure 15.13:** Incorrectly Flat-Fielded Spectrum of the Red G190H Grating



High-precision (S/N > 30) spectroscopic measurements with the FOS require that the observations sample the same portion of the photocathode as do the flatfield calibration observations. This sampling repeatability is limited by the target acquisition accuracy (typically 0.04” for calibration observations) and filter-grating wheel positional repeatability (approximate 1$\sigma$ deviation of 0.04”). The photocathode granularity varies by 5 to 15% over distances as small as 0.2” (see Figure 15.14), and no extended or detailed mapping of the granularity is available in the direction perpendicular to dispersion. Paired aperture granularity is substantially different than that for the single apertures.

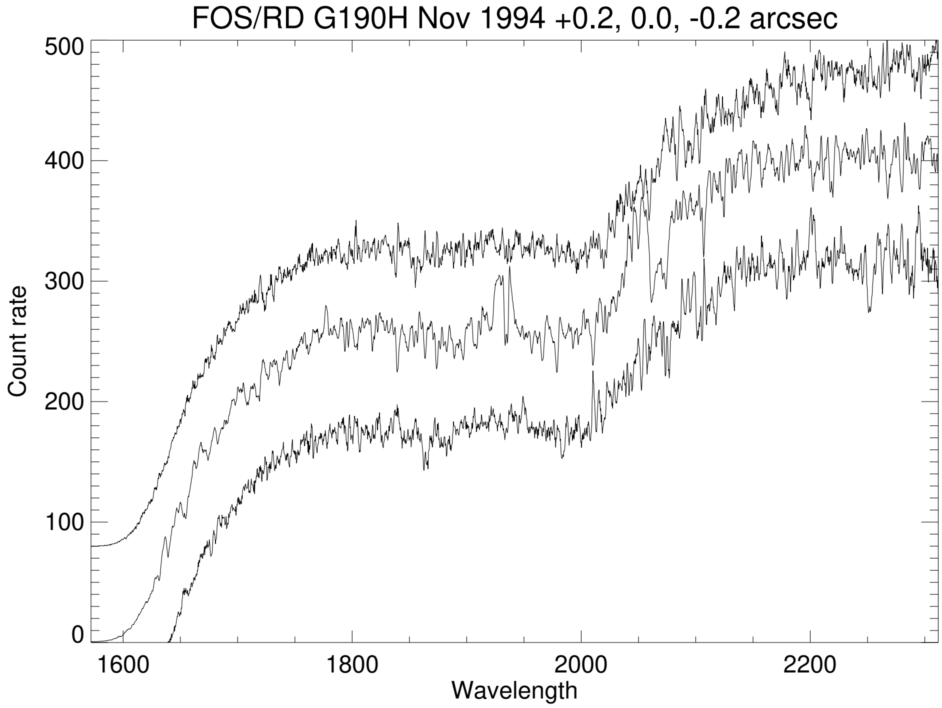
The overall flatfield correction generally has an accuracy of better than 3%, features in certain specific dispersers, apertures, spectral regions, and times of observations may be somewhat poorer as changes may not have been adequately tracked by calibration observations. Table 15.3 provides a list of detector and disperser combinations for which occasional flatfield inaccuracies of ≥5% are known.

One particularly illustrative feature is the strong photocathode blemish that shows up in FOS/BL G160L spectra in the 1500-1560 Å region for all SINGLE apertures. This feature displays a strong spatial dependence such that errors of greater than 20% or more are common after flatfielding. As Figure 15.15 illustrates clearly, this strong blemish is seen in the 4.3” and 1.0” SINGLE aperture spectra and, though slightly weaker, with the 0.3” aperture (which samples a photocathode location concentric with the 1.0” SINGLE), and is very prominent in the 1.0-PAIR-LOWER location (approximately 1.3” below the SINGLE aperture location). However, the feature is nearly absent in the 1.0-PAIR-UPPER spectrum! Due to this striking behavior, the FOS group now recommends that any science observations requiring quantitative analysis of features in the 1500-1560 Å region (notably C IV) should be performed only with the UPPER paired apertures.

Note that also the FOS/RD G190H flatfields have displayed time dependence and substantial spatial dependence in both the pre- and post-COSTAR periods. Please refer to “Flatfield Correction (FLT_CORR)” on page 240 for a more complete discussion of these changes.

Figure 15.14 illustrates the photocathode granularity described above, while Figure 15.15 illustrates the photocathode blemish. Figure 15.14 reflects count rate observations for November 1994 FOS/RD G190H 1.0” aperture observations of the spectrophotometric standard star G191-B2B. From top to bottom, exposures are displaced by +0.20” from the aperture center, well-centered, and displaced by -0.20” from the aperture center. The vertical scale was shifted with no magnification for purposes of display clarity. Figure 15.15 reflects count rate observations for June 1994 FOS/BL G160L observations of the spectrophotometric standard star BD+28D4211. From top to bottom 4.3” aperture, 1.0-PAIR-UPPER, 1.0” single, 1.0-PAIR-LOWER, and 0.3” single apertures. Again, the vertical scale was shifted with no magnification for purposes of display clarity.

**Figure 15.14:** Variations in Photocathode Granularity




Fig, 3d

**Figure 15.15:** Photocathode Blemish at 1500–1560 Å

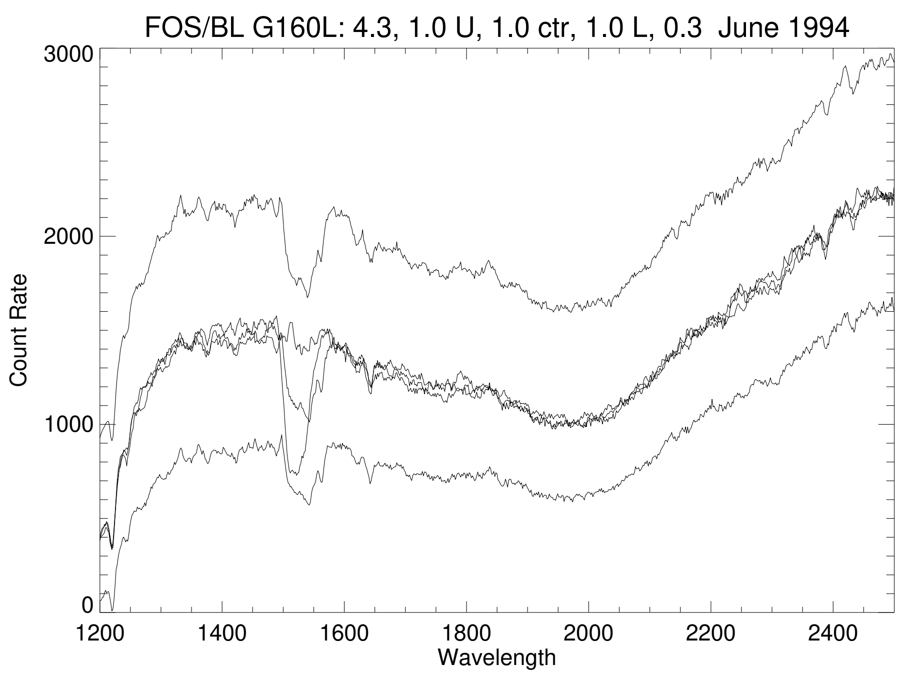


**Table 15.3:** Grating and Detector Combinations with More than 5% Inaccuracy

| FOS/BLUE | FOS/RED |
|---|---|
| G130H | G190H |
| G190H | G270H |
| G270H[a] | G160L |
| G160L[a] | PRISM |

a. Only one pixel range in which 5% deviation occurs.

You should be particularly wary of unusual features in your data. All observers should retrieve the flatfield reference file used to calibrate their data from the HST Archive or STEIS (these files have been delivered routinely on data tapes since May, 1993). As a careful check, compare the flatfield reference file data with:

- Your raw science data.
- The raw count rate data used to produce the flat.
- Any raw count rate data for any other standard stars taken as nearly contemporaneously as possible with your science data in order to assess suspicious features in your science data.

An online reference guide is accessible from both the Advisories Section and the Documentation Section of the FOS world-wide web page on STEIS (`http://www.stsci.edu/ftp/instrument_news/FOS/topfos.html`). This reference guide offers the list of currently recommended flatfield reference files by USEAFTER date for all combinations of detector, disperser, and aperture. Separate guides are maintained for the pre-COSTAR and post-COSTAR periods.

## Under-Subtraction of Background Light

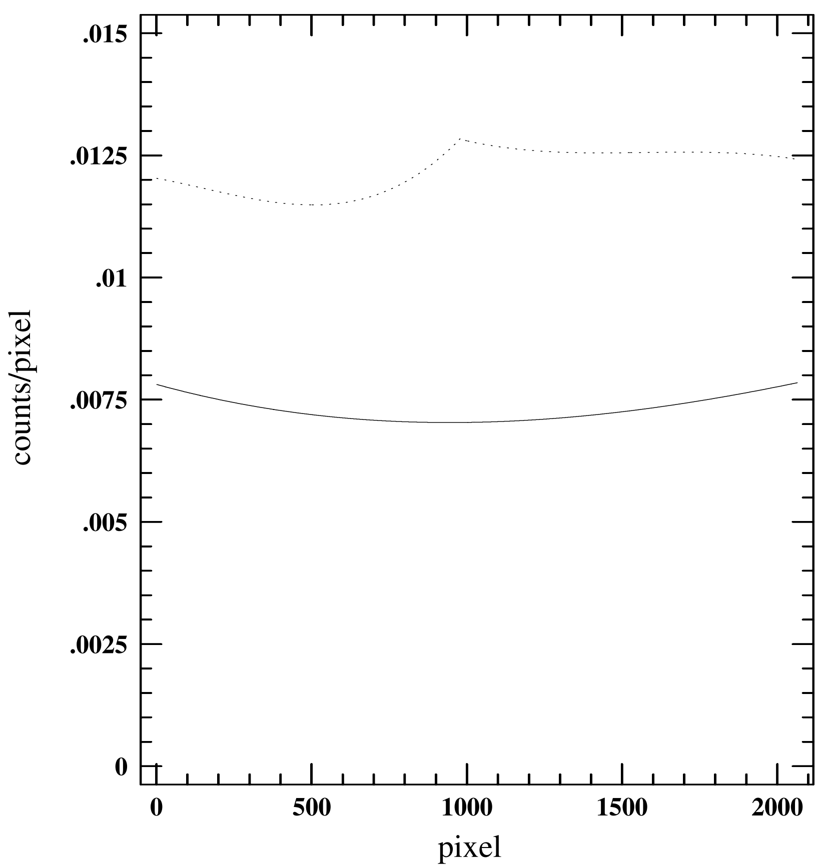
The FOS is subject to two types of background effects caused by high energy particles:

- Light generated by Cerenkov radiation as particles hit the faceplate.
- The striking of the detector by the particles themselves leading to spurious counts.

The default reference background file that is currently used in **calfos** corrects for the dark signal from Cerenkov light. The background reference files are shown in Figure 15.15; both the red (dotted line) and the blue (solid line) detector backgrounds are shown. This model was obtained during Science Verification (see *FOS Instrument Science Reports* 071, 076, 079, and 080) For typical observations, which are obtained with no simultaneous dark data, the background reference file is appropriately scaled to account for the location of the spacecraft in the earth's magnetic field. The scaled background file, which is essentially an estimate of the dark current, is written to the `.c7h` file (in units of counts per second), and subtracted in the pipeline calibration.

It is known that this background has a positional dependence: over the South Atlantic Anomaly (SAA), the background count rate is two orders of magnitude higher than elsewhere in the orbit. Thus, no FOS observations are carried out in the SAA.

**Figure 15.16:** Background Reference Files: Dotted Line is Red Side, Solid Line is Blue Side




The geomagnetic model used to scale the reference background file in the **calfos** pipeline[12] underestimates the background counts by approximately 12% at low geomagnetic latitudes (< 20°) and by about 20-30% at high geomagnetic latitudes. This error is insignificant in the case of strong sources (you can verify this by comparing the counts in the `.c5h` and `.c7h` files), but will cause substantial errors in the derived flux and spectral shape of weaker sources. A V ~ 19 magnitude star with an electron temperature of 10000 K, for example, will have the same count rate as the dark count rate for the FOS/RD detector.

12. *FOS Instrument Science Reports* 099 and 114.

A new background reference file using a more sophisticated charged particle background and geomagnetic field model is currently being developed. For this purpose, all REJLIM=0 IMAGE mode darks from Cycles 1 through 4 were analyzed and relations between the dark count rate and any other variables—specifically, geomagnetic position, solar angle, and time, were investigated. There is little or no correlation between most variables and the dark count rate, except the geo-magnetic latitude. The overall dark count rates are 0.0109 +/– 0.0022 counts/second/diode (FOS/RD) and 0.0064 +/– 0.00083 counts/second/diode (FOS/BL). These numbers are comparable to those quoted in previous versions of the *FOS Instrument Handbook*.

In our preliminary analysis of the geomagnetic latitude dependence of the background count rates we use Singular Value Decomposition (SVD) to make a "best fit" in a least-squares sense, to a polynomial and the data. As we have evidence that the count rate increases with absolute value of the geomagnetic latitude, we use a quadratic as the fitting function.

***FOS/RD:***

$$Rate_{Red} = 8.8 \times 10^{-3} - 8.0 \times 10^{-6} \lambda_{gm} + 5.2 \times 10^{-6} \lambda_{gm}^2$$

***FOS/BL:***

$$Rate_{Blue} = 4.3 \times 10^{-3} + 3.0 \times 10^{-5} \lambda_{gm} + 3.0 \times 10^{-6} \lambda_{gm}^2$$

For observations that have simultaneously-obtained background data, these data are used for background subtraction; and the error due to background subtraction would therefore be the error in the background data.

## Scattered Light

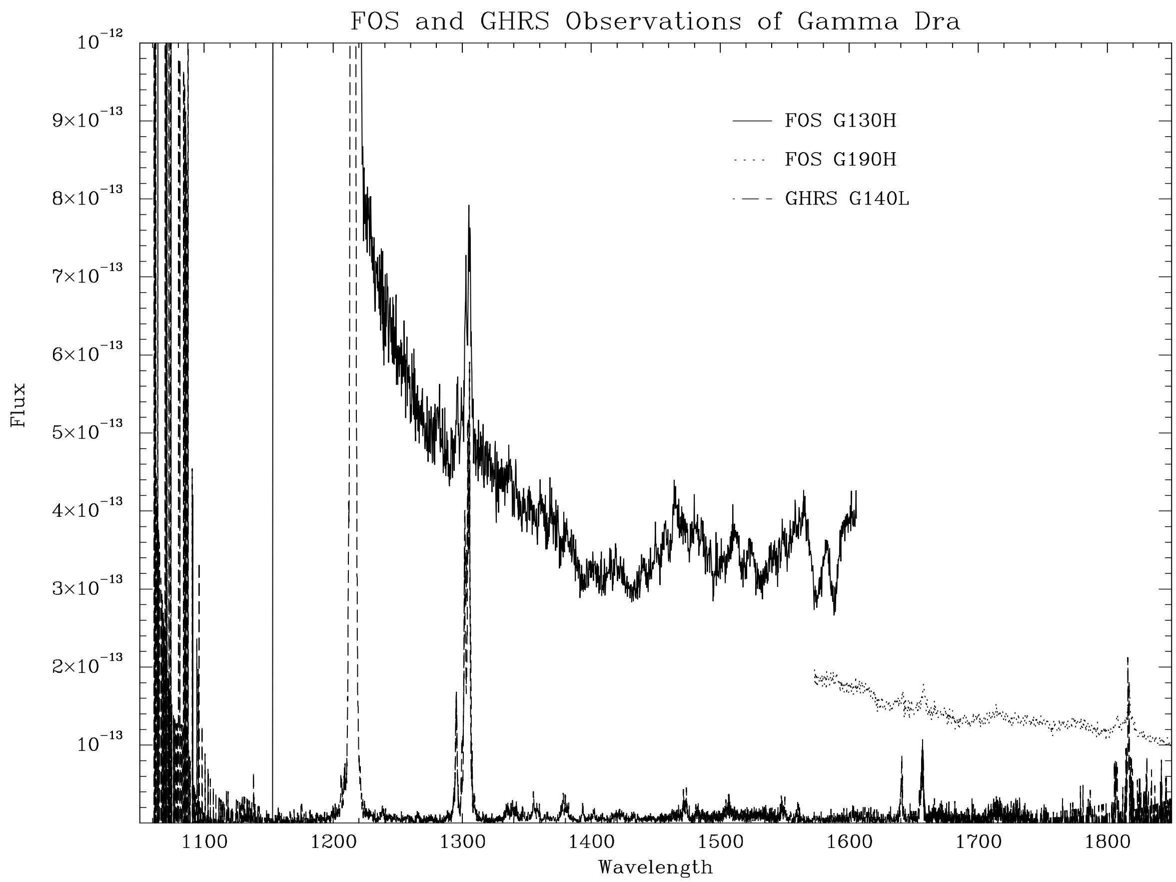
Most scattered light in the FOS is caused by scattering off the gratings and apertures. Pre-flight data taken in the laboratory show that the scattered component increases with increasing wavelength. The G130H, G190H, G270H, G160L, and PRISM spectra (below 2500 Å) are substantially affected by scattered light. A comparison between spectra taken with the solar blind (scatter-free) GHRS and with the FOS shows that the scattered light component dominates the count rate for FOS ultraviolet observations of late type stars (e.g., see Figure 15.17). Thus, scattered light is a major problem for red objects being observed with the short wavelength gratings, where the scattered light photons can dominate the blue photons dispersed by the gratings. For blue objects, the effect of scattered light is less significant.

A model of the scattered light in the FOS was developed by M. Rosa[13]; this model allows a more detailed description of the contribution of scattered light to the observed spectrum depending on the source spectrum (see "Scattered Light Correction (SCT_CORR)" on page 240). This tool, **bspec**, will be made available

13. *FOS Instrument Science Report* 127.

in STSDAS shortly. A comparison of GHRS and FOS spectra (Figure 15.17) and of the **bspec** model predictions with the measurements will then also allow a more accurate assessment of the inaccuracies of the current scattered light correction in the pipeline.

**Figure 15.17:** Scattered Light Comparison of GHRS and FOS



# CHAPTER 16: Recalibrating FOS Data

## In This Chapter...

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Recalibrating FOS Data / 278
Accuracies / 280

This chapter explains the recalibration process and related information, such as finding the most recent information about calibration reference files and instrument changes.

## Finding Reference Files and Calibration Information

If you need to recalibrate your data, the most important information you will need is the names and locations of the appropriate reference files. The relevant file extensions were listed in Table 7.5 on page 222. The location of all available reference files is given in Table 16.1.

**Table 16.1:** STEIS Calibration Listings for FOS

| STEIS Directory and File | Description |
|---|---|
| `/instrument_news/fos/ flat_field_tables_apr93.ps, flat_field_tables_apr93.asc` | Listing of flatfield reference files |
| `/instrument_news/fos/ ivs_tables_jun93.ps, ivs_tables_jun93.asc` | Listing of inverse sensitivity reference files |
| `/instrument_news/ bibliographies/fos_bib` | Bibliography of FOS instrument science reports |

In general, the most up-do-date information on HST can be retrieved from the STScI world wide web pages, using the URL: `http://www.stsci.edu`

The FOS instrument team maintains an area under the FOS web page (URL `http://www.stsci.edu/ftp/instrument_news/FOS/topfos.html`) in which you can look up different kinds of documentation, for example the location of the most up-to-date reference files and the most recent *Instrument Science Reports*.

Another valuable source of general information on the FOS is the current version of the *FOS Instrument Handbook* (6.0). More articles on the FOS can be found in the proceedings of both HST calibration workshops (Blades and Osmer (eds.) 1993; Koratkar and Leitherer (eds.) 1995).

If you cannot find the solution of your problem in this documentation, you can ask for advice via e-mail to `help@stsci.edu`. The *FOS Instrument Handbook* also lists the names, e-mail addresses, and phone numbers of the FOS Instrument Scientists and Data Analysts, who might be able to assist you.

Many problems occur repeatedly and some questions pertain to so many practical cases that they are asked very frequently. Therefore, we have compiled both a list of frequently asked questions (FAQ), which is available on one of our web pages, as well as several short "cookbooks" describing standard procedures to handle certain situations. These cookbooks are intended to give specific advice on special data reduction issues: they provide relatively detailed answers to frequently asked questions. They are not intended as formal publications, like the *FOS Instrument Science Reports*. A list of available cookbooks is provided on page 301.

# Recalibrating FOS Data

The IRAF/STSDAS task used for both calibrating or recalibrating FOS spectra is **calfos**. The task sequentially performs each step described in "Overview of the FOS Pipeline Process" on page 244. To recalibrate FOS data using updated calibration files, you need to edit the header of the original science data, `.d0h`, (using the task **hedit**) and replace the names of the original calibration files with those of the new ones.

The first thing to do is make sure that your data are flux calibrated with the new AIS method. The STSDAS task **addnewkeys** will update the headers of your `.d0h` files accordingly. In order to enter into the headers the most recent calibration and reference files and tables, use the task **getreffile**.[1] You can pipe the output directly into the routine **upreffile**, which will update the file headers:

```
getreffile @inputfile.list | upreffile
```

After doing this, check the file headers carefully and make sure that all calibration switches are set properly. Once this is done you can rerun **calfos**.

1. The **getreffile** task is available only at STScI because it uses the Calibration Database (CDBS) which is not part of STSDAS. Alternatively, the files can be retrieved from the HST Archive.

**Figure 16.1:** Partial Post-COSTAR FOS Header

```
/ CALIBRATION FLAGS AND INDICATORS
GRNDMODE= 'RAPID-READOUT     ' / ground software mode
DETECTOR= 'BLUE              ' / detector in use: amber(red), blue
APER_ID = 'A-1               ' / aperture id
POLAR_ID= 'C                 ' / polarizer id
POLANG  =                  0.0 / initial angular position of polarizer
FGWA_ID = 'H13               ' / FGWA id
FCHNL   =                    0 / first channel
NCHNLS  =                  512 / number of channels
OVERSCAN=                    5 / overscan number
NXSTEPS =                    4 / number of x steps
YFGIMPEN=                    T / onboard GIMP correction enabled (T/F)
YFGIMPER= 'NO                ' / error in onboard GIMP correction (YES/NO)

                 / CALIBRATION REFERENCE FILES AND TABLES
DEFDDTBL=                    F / UDL disabled diode table used
BACHFILE= 'yref$b3m1128my.r0h' / background header file
FL1HFILE= 'yref$e7813577y.r1h' / first flat-field header file
FL2HFILE= 'N/A               ' / second flat-field header file
IV1HFILE= 'yref$e3h1449qy.r2h' / first inverse sensitivity header file
IV2HFILE= 'N/A               ' / second inverse sensitivity header file
RETHFILE= 'N/A               ' / waveplate retardation header file
DDTHFILE= 'yref$d9h1244ay.r4h' / disabled diode table header file
DQ1HFILE= 'yref$b2f1306ry.r5h' / first data quality initialization header file
DQ2HFILE= 'N/A              ' / second data quality initialization header file
CCG2    = 'mtab$a3d1145ly.cmg' / paired pulse correction parameters
CCS0    = 'ytab$a3d1145dy.cy0' / aperture parameters
CCS1    = 'ytab$aaj0732ay.cy1' / aperture position parameters
CCS2    = 'ytab$a3d1145fy.cy2' / sky emission line regions
CCS3    = 'ytab$a3d1145gy.cy3' / bkg and sky filter widths
CCS4    = 'ytab$e5v13262y.cy4' / polarimetry parameters
CCS5    = 'ytab$a3d1145jy.cy5' / sky shifts
CCS6    = 'ytab$e5v11576y.cy6' / wavelength coefficients
CCS7    = 'ytab$ba910502y.cy7' / GIMP correction scale factors
CCS8    = 'ytab$ba31407ly.cy8' / predicted background count rates
CCS9    = 'ytab$e3i09491y.cy9' / scattered light parameters

                 / CALIBRATION SWITCHES
CNT_CORR= 'COMPLETE'           / count to count rate conversion
OFF_CORR= 'OMIT              ' / GIMP correction
PPC_CORR= 'COMPLETE'           / paired pulse correction
BAC_CORR= 'COMPLETE'           / background subtraction
GMF_CORR= 'COMPLETE'           / scale reference background
SCT_CORR= 'COMPLETE'           / scattered light correction
FLT_CORR= 'COMPLETE'           / flat-fielding
SKY_CORR= 'SKIPPED '           / sky subtraction
WAV_CORR= 'COMPLETE'           / wavelength scale generation
FLX_CORR= 'COMPLETE'           / flux scale generation
ERR_CORR= 'COMPLETE'           / propagated error computation
MOD_CORR= 'PERFORM           ' / ground software mode dependent reductions
```

**calfos** will create new calibrated output files with the same extensions as the originally delivered data, namely .cnh and .cnd (n=0...8).[2]

You should always compare the final calibrated data with the various reference files used in the data reduction process to make sure that spurious features were not introduced through improper data handling in the pipeline or your recalibration.

If you use the proper reference files, you can expect to achieve the following accuracies for FOS spectra.

2. More details on updating file headers are available in a cookbook available from the Help Desk.

# Accuracies

In this section, we summarize what is known about the accuracies of calibrated FOS data. We point out any known systematic effects in the determination of the photometric scale which may affect the flux calibration of your FOS data. Described here are:

- Wavelength accuracies.
- Photometric accuracies.
- Polarimetric accuracy.

## Wavelength Accuracy

The *vacuum* wavelength scale is computed during the pipeline processing, and the derived wavelengths for each dataset are stored in the `.c0h` file. Internal wavelength calibration lamps are used to determine the dispersion coefficients corresponding to each disperser and detector combination. The rms errors in the dispersion relations range between 0.01–0.08 diodes.[3]

This, together with a non-linearity of the diode array of about 0.02 diodes (rms), is the physical hard limit for the achievable accuracy of the wavelength calibration for the FOS. Even if the target is well centered in the aperture, the highest possible accuracy can be achieved only if wavelength calibration spectra are taken together with the science data. If you choose to only use wavelength data from the Archive, the calibration accuracy is determined by non-repeatabilities of the filter grating wheel (FGW)—and the aperture wheel, if it should be moved during the observations.

The FGW non-repeatability introduces an error of ~0.1 diodes. This corresponds to ~60 km $s^{-1}$ for the high dispersion gratings. On average no large temporal shift has been observed for the wavelength calibration for any disperser and detector combination. Residual inaccuracies in the magnetic deflection after GIM correction can also occasionally lead to wavelength calibration non-repeatabilities of about 0.1 diodes.

Since the light path of an external source is offset slightly from that of the internal calibration lamps, a correction for this offset has to be taken into account in the absolute wavelength calibration. Observations of a radial velocity standard source are then used to determine the zero point (internal-to-external offsets) of the wavelength scale. The internal-to-external offsets of the FOS wavelength calibration are 0.102 +/– 0.1 diodes for the blue side and 0.176 +/– 0.105 diodes for the red side. Hence, including the non-repeatabilities mentioned above, the accuracy with which the zero point of the wavelength scale is known in an individual spectrum is ≤ 0.25 diodes.

A new wavelength calibration, based on more than 10 post-COSTAR observing epochs, is currently being developed. Preliminary results show no systematic change due to the deployment of COSTAR. However, based on the

3. *FOS Instrument Science Report 0*67.

larger number of observations compared to the old pre-COSTAR wavelength calibration (Kriss et al., 1990)[4], outliers will be identified and thus a higher accuracy will be reached with the new reference tables.

### *Overlap Region of Adjoining Gratings*

The wavelength calibration uncertainty does not exceed more than 0.5 diodes in the overlap regions of the various gratings. This uncertainty is due to the lack of an arc comparison line in the overlap region of the gratings, where the wavelength solution is an extrapolation. Note that an error in the wavelength calibration introduces a small (<1%) error in the flux calibration.

## Photometric Accuracy

Reminder: All FOS observations should always be re-processed with the most current AIS_CORR reference files and tables.

The FOS flux calibration is obtained from carefully centered (≤0.04” pointing accuracy) and flatfielded observations of spectrophotometric standard stars. Five standard stars, G191-B2B, BD+28D4211, BD+33D2642, BD+74D325, and HZ44, were used for the pre-COSTAR calibration observations. For the post-COSTAR calibrations, this set and three more white dwarf standards, GD71, GD153, and HZ43 are used. All pre-COSTAR observations were made with the 4.3” aperture and post-COSTAR observations are made with either the 4.3” or the 1.0” aperture. Typical S/N of binned spectral regions for these observations are 100 or often substantially greater.

Two methods of flux calibration have been used. All pre-COSTAR data reduced in the pipeline were reduced with the FLX_CORR method. One average set of sensitivity corrections was applied to all pre-COSTAR data regardless of when the data were taken or how far the telescope may have been from nominal focus. Since Fall 1994 (about one year after servicing) a second method of flux calibration has been available for pre-COSTAR Archive data—the so-called AIS_CORR method, which includes corrections for time-dependent sensitivity variations and includes corrections for the actual focus history of the telescope.

All post-COSTAR observations prior to fall of 1995 have also been calibrated in the pipeline with the FLX_CORR method. Beginning in the fall of 1995 the AIS_CORR method will be the default method for pipeline calibration. The FLX_CORR IVS corrections for 4.3” and 1.0” apertures were derived from post-COSTAR observation, but FLX_CORR IVS curves for all other apertures were calculated from theoretical aperture throughputs. All AIS_CORR corrections are based on actual post-COSTAR observations. Some small aperture FLX_CORR sensitivities may differ from AIS_CORR by up to 10% in selected ultraviolet spectral regions. The effects of focus and time-dependent sensitivity

4. Ibid.

variation are much less severe for the post-COSTAR era, but improvement is always obtained with AIS_CORR.

Pre-COSTAR FLX_CORR method (the standard pipeline reduced data) photometry is substantially inferior to fluxes derived from the new AIS_CORR method. Several important sources of photometric error could not be removed in the pipeline processing, but can be calibrated quite accurately by reprocessing with AIS_CORR. For example, pre-COSTAR FLX_CORR pipeline-calibrated fluxes may contain errors of up to 5% (FOS/RD) or up to 8% (FOS/BL) due to the pre-COSTAR sensitivity decline, of 5% due to telescope focus changes, and 3-15% (depending on spectral region) due to the offset between the IUE-based absolute flux system and the newer white dwarf model system. All of these error sources can be removed by re-calibration with AIS_CORR.

Post-COSTAR FLX_CORR method photometry, which is on the white dwarf absolute system, typically differs from the recommended AIS_CORR re-processing by <3% for large apertures, but, as noted above, may be in error by up 10% for the smallest apertures and shortest wavelengths.

The overall uncertainty of the AIS_CORR FOS flux calibration for point sources is ≤3% (Bohlin et al. 1995).[5]

Additional sources of photometric error that can not be removed with the improved AIS_CORR processing are listed in Table 16.2. Approximate levels of error introduced are given for both the pre- and post-COSTAR cases.

**Table 16.2:** FOS Photometric Errors Not Removed by AIS_CORR

| | Level of Error | | |
|---|---|---|---|
| **Source of Error** | **Pre-COSTAR** | **Post-COSTAR** | **Comment** |
| Miscentering target in aperture | ~5% | ~3% | Depends on target acquisition technique and aperture used. Error can be easily estimated. |
| y-location of spectra | 3-10% | 1-10% | Strongly affects extended objects |
| Thermal breathing | ~4% | ~1% | Aperture dependent |
| Jitter | <3% | <1% | Aperture dependent |
| GIM[a] | <5% | <1% | |

a. Pre-COSTAR GIM estimate refers to period before April 5, 1993.

5. The PODPS inverse sensitivity files used in the pipeline before March 1992 were prelaunch estimates and are incorrect by a factor of 2-3 because the spherical aberration and the real performance of the photocathode in space were not considered. Prior to March 1993, there were some uncalibrated apertures for which the inverse sensitivity files were prelaunch estimates. As of March 1993, new reference files with sensitivity set to 1 were installed for the uncalibrated apertures and any data calibrated with these files will remain in units of count rates and are not flux calibrated. In the post-COSTAR period, but before March 21, 1994, unity IVS files were used for all combinations of detector, disperser, and aperture—only three programs were affected. Unity IVS continue to be used for all barred apertures. AIS_CORR files will be ready for use in 1996. Before AIS_CORR, some post-COSTAR small aperture fluxes are in error by <10%.

## Polarimetric Accuracy

For polarimetric observations the light beam in the FOS is split up right behind the entrance aperture by a Wollaston prism. One of the two resulting rays (the first and second pass, see "Polarimetric Calibration" on page 256), is rotated into one plane with the other by a waveplate so that both spectra are directed parallel to each other on the photocathode. These optical elements add only negligible errors to polarization data. The errors are dominated by the same errors as mentioned above for photometric measurements, i.e., filter-grating wheel non-repeatability, residual uncertainty of the magnetic field after GIM correction (which leads to uncertainties in the y location of the spectra), and aperture wheel non-repeatability. The two COSTAR mirrors add an instrumental polarization of $\leq 2\%$ compared to pre-COSTAR data. After subtraction of this component, polarimetric accuracies of $\leq 1\%$ can be achieved. For bright objects, the polarization angles are known to within about +/-5 degrees. An *FOS Instrument Science Report* on this topic is currently in preparation.

# CHAPTER 17:
# Specific FOS Calibration Issues

**In This Chapter...**


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RAPID Mode Observation Timing Uncertainties / 288


This chapter describes some specific issues relating to the FOS instrument and the calibration of its data.

## Effects of COSTAR on FOS Data

The FOS is one of the HST instruments that are only moderately affected by the COSTAR deployment. Owing to the narrower point spread function (PSF) of the telescope, the throughput of a given aperture for point sources is higher now than in the past. For example, the throughputs of the 4.3”, 1.0”, and 0.3” apertures went up by factors of 1.3, 2.0, and 2.5, respectively. The narrower PSF more selectively illuminates fine-scale photocathode granularity rather than smoothing it out as was the case pre-COSTAR. As a result, very precise target acquisitions are needed to achieve high flatfielding accuracy.

The narrower PSF also leads to a slightly narrower line spread function (LSF) for post-COSTAR data compared to the pre-COSTAR era. In addition, the size of the diodes projected on the sky has changed slightly because of the change in focal length of the instrument (1″.29 post-COSTAR vs. 1″.43 pre-COSTAR). Polarimetric measurements are affected, because additional optical elements (mirrors) were introduced into the light path, and this changes the characteristics of the incoming wavefronts. On the other hand, the wavelength calibration appears not to have been measurably affected.

Thus, although some details in the FOS instrument characteristics have changed, the overall performance is not severely affected by COSTAR. Some of these changes have been discussed here, others still need to be quantified and have yet to be published—check our online documentation on the world wide web frequently; this is where the most recent results and publications will be listed.

## Aperture Dilution Correction for Extended Sources

Flux calibrations are determined from observations of standard stars and compensate automatically only for any light in the PSF that falls outside the aperture. For observations of *extended* sources, a correction needs to be applied to the final flux calibrated spectrum to correct for the different illumination pattern. The correction is given by

$$I = \frac{F \times A\,(ap) \times T_{4.3}}{\Omega}$$

where:

- $I$ = Specific surface intensity of a diffuse source in ergs $s^{-1}$ $cm^{-2}$ $Å^{-1}$ $arcsec^{-2}$.
- $F$ = Flux in the calibrated spectrum.
- *A(ap)* = Relative point source transmission through the aperture area when $A(4.3) \equiv 1$. These are given in Table 17.1.
- $\Omega$ = Solid angle of the aperture in square arcseconds, e.g., 4.3″ x 1.4″ (pre-COSTAR) and 3.7″ x 1.3″ (post-COSTAR) for the 4.3″ aperture.
- $T_{4.3}$ = Absolute transmission for a point source at zero focus of the 4.3″ aperture. This number cannot be measured directly but is estimated to be ~0.73 (pre-COSTAR) and 0.95 (post-COSTAR).[1] More details are provided in a cookbook available from the Help Desk (`help@stsci.edu`).

**Table 17.1:** Recommended Pre-COSTAR Aperture Corrections and Uncertainties at Nominal OTA Focus

| Grating | BLUE | RED | UNC[a] | BLUE | RED | UNC | BLUE | RED | UNC | BLUE | RED | UNC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mode | | B3 (1″) | | | B1 (0.5″) | | | B2 (0.3″) | | | C2-SLIT | |
| HIGH | 0.58 | 0.60 | .02 | 0.41 | 0.44 | .02 | 0.27 | 0.31 | .03 | 0.39 | 0.41 | .02 |
| LOW | 0.65 | 0.67 | .06 | 0.46 | 0.50 | .04 | 0.31 | 0.35 | .03 | 0.43 | 0.45 | .03 |
| PRISM | 0.53 | 0.54 | .06 | 0.37 | 0.39 | .04 | 0.26 | 0.30 | .03 | 0.37 | 0.39 | .03 |

a. The uncertainties (UNC) do not include the possible contributions of pointing errors, OTA breathing, jitter, or Y-base errors in an arbitrary science observation.

1. See *Instrument Science Reports* 106 and 107.

The deployment of COSTAR cause a narrower PSF, which led to considerably higher throughputs of the apertures to change considerably. For the large apertures (1.0” and larger) there is no measurable difference between FOS/RD and FOS/BL. Therefore, we list both detectors separately only for the 0.3” aperture and the slit in Table 17.2 The wavelength (grating), for which the throughputs are measured plays a more important role. Therefore, we list here ratios for the different dispersers separately. The numbers are taken from Bohlin and Colina (1995).[2]

**Table 17.2:** Post-COSTAR Average Aperture Throughput Ratios Relative to A-1

| | BLUE and RED | BLUE and RED | BLUE | RED | BLUE | RED |
|---|---|---|---|---|---|---|
| **Grating** | **B3 (1″)** | **B1 (0.5″)** | **B2 (0.3″)** | | **C2-SLIT** | |
| G130H | 0.875 | 0.730 | 0.640 | --- | 0.615 | --- |
| G190H | 0.900 | 0.810 | 0.720 | 0.720 | 0.715 | 0.715 |
| G270H | 0.920 | 0.870 | 0.780 | 0.790 | 0.745 | 0.770 |
| G400H | 0.950 | 0.890 | 0.800 | 0.830 | 0.780 | 0.800 |
| G570H | 0.960 | 0.890 | --- | 0.840 | --- | 0.810 |
| G780H | 0.960 | 0.895 | --- | 0.780 | --- | 0.820 |
| G160L | 0.895 | 0.790 | 0.700 | 0.720 | 0.675 | 0.720 |
| G650L | 0.955 | 0.900 | --- | 0.840 | --- | 0.795 |
| PRISM | 0.910 | 0.835 | 0.730 | 0.770 | 0.720 | 0.760 |

Information on the data quality is stored in the `.cqh`, `.c2h`, and `.c3h` files. The `.c2h` file contains propagated statistical errors, assuming Poisson statistics, the `.c3h` file is a special statistics file that is produced for RAPID and PERIOD mode and for spectropolarimetric data. For RAPID and PERIOD data, the `.c3h` contains total or average fluxes for each frame and associated statistical errors. The data quality flags used for FOS data are compiled in Table 17.3.

2. *FOS Instrument Science Report* 136.

**Table 17.3:** FOS Data Quality Flag Values (Calibrated Data)

| Flag Value | Description |
|---|---|
| | ***Category 1: Data not useful. Data values set to zero.*** |
| 800 | Data filled |
| 700 | Data filled due to GIM correction |
| 400 | Disabled channel |
| 300 | Severe saturation (uncertainty greater than 50%) |
| 200 | Inverse sensitivity invalid ($\lambda$ < 1100 Å or $\lambda$ > 7000 Å) |
| ***Category 2: Data Uncertain. Uncertainty not Indicated in Error Calc.*** | |
| 190 | Large saturation correction (uncertainty greater than 20%) |
| 170 | Intermittent noisy channel |
| 160 | Intermittent dead channel |
| 130 | Moderate saturation correction (uncertainty greater than 5%) |
| 120 | Sky or background fixed or extrapolated |
| 100 | Reed-Solomon decoding error |
| ***Category 3: Data uncertain. Uncertainty in propagated error file*** | |
| 50 | Sampling less than 50% of nominal |

Many other useful tasks (besides **calfos**) for handling FOS data can be found in the IRAF/STSDAS package; see Chapter 2 for more details. There you can find the names and brief descriptions of those tasks which are most important for spectroscopy.

# RAPID Mode Observation Timing Uncertainties

Under certain very specific and rather complicated circumstances, the start times of individual exposures in an FOS RAPID mode time series must be calculated in a special manner. We recommend that RAPID mode observers contact the Help Desk (e-mail: `help@stsci.edu`) for help in determining precise start times of their exposures.