Part VI

Faint Object Spectrograph

In This Part...

The chapters in this part deal exclusively with information about the Faint Object Spectrograph. The Practical Guide provides examples of sample datasets, shows you what to expect in an FOS dataset, describes various problems that may occur in the data, and provides information needed to correct these problems. The FOS Details chapter provides detailed information about target acquisition modes, exposure times, aperture orientation, and the pipeline calibration algorithms.

16 Practical Guide to FOS Processing

In This Chapter...

This chapter[1] is a practical guide to help you work with your Faint Object Spectrograph (FOS) data. It describes FOS observational parameters, the operation of the instrument, and provides you with the information you need to understand the accuracy of your calibrated FOS data and to identify and correct problems with your data. This chapter is divided into the following major sections:

- What to expect.
- FOS basics.
- Data accuracies.
- Sources of photometric errors.
- Data errors.

What to Expect

The goal of this section is to familiarize you with the basic characteristics of data taken with the FOS.

1. This chapter was written by Anuradha Koratkar.

Overview

The Faint Object Spectrograph is used to obtain intermediate resolution spectra (resolving power R=1300 or 250) over the wavelength range 1150 to 8500 Å. A polarizer allows measurement of linear and circular polarization. Spectra can be taken in several different modes, including:

- ***ACCUM mode***: Used for spectrophotometry (identified by the keyword values OPMODE=ACCUM, and GRNDMODE=SPECTROSCOPY) and spectropolarimetry (identified by the keywords OPMODE=ACCUM, and GRNDMODE=SPECTROPOLARIMETRY).
- ***RAPID mode***: Used for high time-resolution spectrophotometry (identified by keyword values OPMODE=RAPID, and GRNDMODE=RAPID READOUT).
- ***PERIOD mode***: Used to produce high time-resolved spectra which are binned according to a known periodicity (identified by the keywords OPMODE=PERIOD, and GRNDMODE=TIME-RESOLVED).

Spectra taken by the FOS are almost always time resolved[2] and so each observation contains multiple spectra which are written to multiple groups in the image (`.c1h` and `.c0h` files).

The most commonly-used modes of the FOS are ACCUM and RAPID mode, which differ only in the way the data are accumulated and stored in the resulting image. In ACCUM mode, the data from each subintegration are co-added and stored in groups so that the *n*th group contains the co-added (accumulated) data from subintegrations 1 through *n*, and the last group contains the *accumulated* spectrum for the entire observation. Thus, for ACCUM mode data, observers will normally want to work with the last group which contains the spectrum with the full exposure time for the observation. In RAPID mode, the subintegrations are not co-added; the *n*th group contains data only from the *n*th sub-integration. PERIOD mode and spectropolarimetry are described in detail in the "FOS Basics" chapter, see pages 256 and 253, respectively.

Table 16.1 lists the basic FOS header keyword parameters.

2. Even ACCUM mode data are usually taken in a time-resolved fashion to avoid catastrophic loss of data.

Table 16.1: Important FOS Header Keywords

Keyword	Description and Comments
GCOUNT	Number of groups in the data file
INSTRUME	Instrument used for the observation
ROOTNAME	Rootname of the observation set
FILETYPE	Type of data in the file
GRNDMODE	Ground software mode
DETECTOR	Detector in use for the observation
OPMODE[a]	Operation mode of the FOS for the observation
APER_ID	Aperture used for the observation
POLAR_ID	Polarization waveplate used for the observation
FGWA_ID	Filter-grating wheel position used for the observation
PA_APER	Position angle of the aperture in degrees
RA_APER1	RA of aperture center in degrees
DECAPER1	Declination of aperture center in degrees
NCHNLS	Number of diodes used in the observation
OVERSCAN	Number of overscans used in the observation
NXSTEPS	Number of X substeps used in the observation
FPKTTIME[b]	Readout time of the first data packet sent to the SDF for each group, i.e., time at the *end* of each group observation. The units are modified Julian date.
DATE-OBS	FPKTTIME for group 1 converted to standard notation for date
TIME-OBS	FPKTTIME for group 1 converted to standard notation for time
EXPSTART	Exposure start time in modified Julian date
EXPOSURE[b]	Exact exposure time per pixel in seconds for each group of data
EXPTIME	Exposure time for complete observation (i.e., total time that FOS accumulated photons during observation)

a. In the `.shh` file.
b. Group parameter.

FOS Basics

In this section we describe the basic operation of the FOS. Included here are a description of

- The instrument.

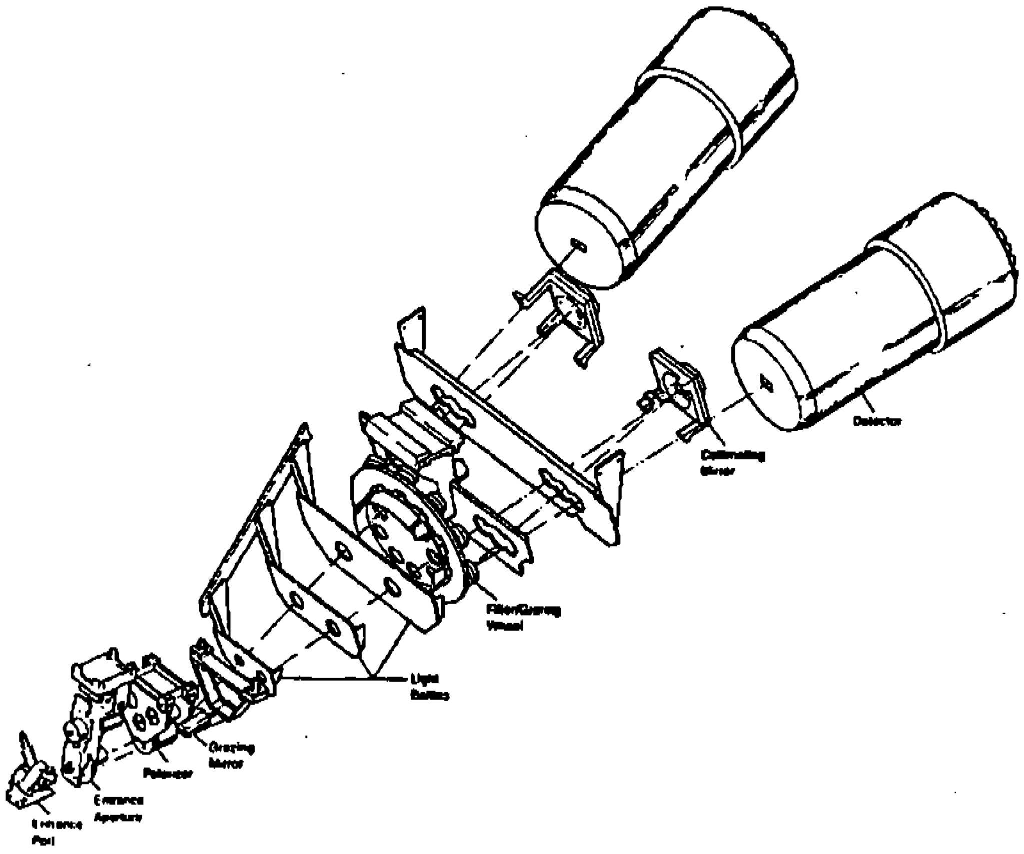
- Substepping and overscanning.
- Exposure times.
- Target acquisitions.

The Instrument

The FOS is composed of two Digicon detectors with independent optical paths, the blue (BLUE) side (identified by header keyword CONFIG=FOS/BL), which is sensitive to light from 1150 to 5400 Å and the red (or AMBER) side (identified by keyword CONFIG=FOS/RD), which is sensitive to light from 1620 to 8500 Å (see Figure 16.1). Light entering the FOS passes through the aperture wheel which controls the aperture choice (identified by header keyword APER_ID[3], a polarizer (identified by keyword POLAR_ID) which has a clear position, and the filter-grating wheel. In the filter-grating wheel the light is either dispersed by a concave grating or a camera mirror plus prism, or is reflected by a camera mirror (identified by keyword SPEC_1 (or FGWA_ID). The light focuses onto a two dimensional transmissive photocathode in the Digicon detector.

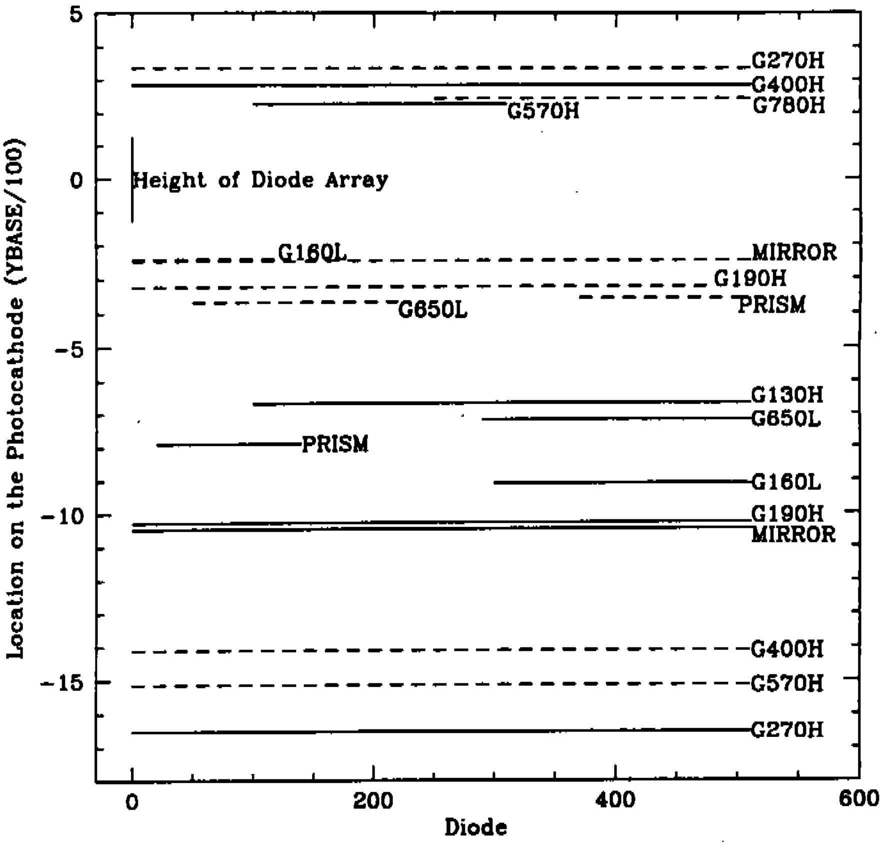
3. Or APER_1 in the .shh file.

Figure 16.1: FOS Optical Path



The photocathode is a two dimensional detector (X is the dispersion direction, Y the spatial direction). The photocathode extends from −2047 Y-base units to +2048 Y-base units (256 Y base units is approximately the height of the diode array). Each disperser produces its spectrum at a different location on the photocathode. The locations of the red (dashed line) and blue (solid line) dispersed spectra are shown in Figure 16.2. The photoelectrons from the region of the photocathode where the image is expected are then accelerated to a linear array of 512 diodes. There the counts are accumulated for an interval of time (typically 512 milliseconds) until the data (counts per diode) are read out into memory in the FOS microprocessor. The FOS diode array is scanned in a pattern determined by the data acquisition mode.

Figure 16.2: Location of Spectra on the Photocathode. Dashed Lines Represent Red Detector, Solid Lines Represent Blue Detector



Substepping and Overscanning

There are two techniques commonly employed in the use of the FOS to obtain spectra; *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 an additional 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 spectrum is deflected an additional whole diode in the dispersion direction. A complete round of substepping is performed following each overscan step. The number of overscan steps performed before returning to the original diode location is determined by the overscan parameter (header keyword

OVERSCAN). The data taken at different overscan positions but at common substep positions are co-added in the memory of the FOS microprocessor. 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 contribute to a single pixel. The combination of overscanning and substepping means that a given diode will have contributed to the data in (NXSTEPS x OVERSCAN) pixels.

For ACCUM mode, the default value of NXSTEPS=4 and OVERSCAN=5. Thus, a typical ACCUM mode spectrum has 2064 pixels.

Times

The basic times most observers will be interested in are:

- Start and end times (of the observation, or of the integration for a given group).
- Exposure time per pixel (i.e., the integration time which contributes to the counts in each pixel), for the whole observation, or a given group.

In this section, we describe how to determine these values. Table 16.2 summarizes the information explained below. A more complete description of exposure times and how they relate to pattern keywords is given in "Calculating Exposure Times" on page 264.

Table 16.2: Timing Information for FOS

Type of Information	Source	Units
Observation start time	EXPSTART[a]	Modified Julian date
Group start time	FPKTTIME[b] – group_elapsed_time	Modified Julian date
Group_elapsed_time	FPKTTIME (group 1) – EXPSTART	Seconds
Group exposure time per pixel	EXPOSURE[b]	Seconds
Group end time	FPKTTIME[b]	Modified Julian date
Observation end time	FPKTTIME[b] (last group)	Modified Julian date

a. Header keyword
b. Group parameter

Observation start and stop times are determined with a precision of 1/8 second, while exposure times are determined with a precision of 7.8125 microseconds.

Start and End Times

The start time of the observation (i.e., the time at which the integration was begun for the first group of data) is given in modified Julian date in the header keyword EXPSTART. The modified Julian date is the Julian date minus 2400000.5.

You can use the STSDAS task **epoch** (in the **toolbox.tools** package) to covert this time from modified Julian date to the standard date time notation.

The *end* time of the integration for each group of data is given in modified Julian days in the group parameter FPKTTIME. The end time of an observation is the FPKTTIME of the last group of the observation. To calculate the group start time, subtract the *group elapsed time* from FPKTTIME. The group elapsed time (which will be the same for all groups in a given observation) can be calculated as FPKTTIME for the first group of data minus EXPSTART. The start time of each subsequent group is then given as FPKTTIME for that group minus the group elapsed time (see Table 16.2.

Exposure Times

The *elapsed time* for an observation differs from the *exposure time* (the actual integration time during which counts are accumulated) because the elapsed time includes the deadtime during which the FOS is doing housekeeping (e.g., reading out the diodes) and is therefore not integrating. The total *exposure time* for the entire observation (all groups) is given by the keyword EXPTIME in the data header.

The *exposure time per pixel*, the integration time which contributed to the flux observed in a given pixel, differs from the exposure time for the spectrum whenever substepping is employed. The exposure time is divided among the NXSTEPS individual substepped spectra which together produce the single spectrum. The (typical) exposure time per pixel is therefore given by the exposure time divided by NXSTEPS. This quantity is in the group parameter EXPOSURE.[4]

Target Acquisitions

FOS data can be obtained through several different apertures, ranging from 0.1 arcsecond to 4.3 arcseconds in size for pre-COSTAR data. The target is centered in the chosen aperture using one of three methods:

- Blind pointing.
- One of the target acquisition techniques that determine the location of the target relative to the aperture center by measuring the location of the target image on the photocathode.
- Via an interactive or WF/PC-assisted early acquisition.

The 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).

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4. Note, however, that the actual exposure time for a given pixel may be different from EXPOSURE, either because the pixel did not receive input from OVERSCAN diodes (because they are edge pixels or because they are fed by input from one or more disabled diodes), or because a particular readout was rejected by the onboard burst noise rejection algorithm. Thus EXPOSURE actually reports the maximum possible exposure time per pixel. The **calfos** task correctly calculates the count rate of each pixel, taking into account the number of diode readouts which contributed to the counts observed in each pixel, using the information in the disabled diode reference table to compensate for disabled diodes and the noise rejections tallied in the reject array (the .d1h file) to compensate for times when the counts from a particular diode were not accumulated into memory due to noise rejection (see also page 269).

Target acquisition observations produce science data sets. Thus, for each set of FOS observations of a given source the first dataset will be the FOS target acquisition image.[5] This image will be easily identifiable, because the header keyword GRNDMODE will be set to TARGET ACQUISITION, 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. A more complete description of target acquisitions, the data they produce, and how to analyze these data is given in Chapter 17 on page 245.

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.

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.[6] 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. The filter grating wheel non-repeatability introduces an error of ~0.1 diodes. Hence, the

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

6. *FOS Instrument Science Report* 67. A complete list of FOS Instrument Science Reports is found on page 289.

accuracy with which the zero point of the wavelength scale is known in an individual spectrum is ≤ 0.25 diodes. This corresponds to ~60 km/sec for the high dispersion gratings. On average no large temporal shift has been observed for the wavelength calibration for any disperser and detector combination.

Overlap Region of Adjoining Gratings

The wavelength calibration uncertainty does not exceed more than 0.1 diodes in the overlap regions of the various gratings. This uncertainty is sometimes 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

The flux calibration is done from carefully centered and flat fielded observations of spectrophotometric standards G191-B2B, BD+33D2642, BD+28D4211, BD+75D325 and HZ-44 in the 4.3″ aperture for all disperser and detector combinations. Observed standard star spectra used for inverse sensitivity measurements are good to 1%. The FOS BLUE photometry is good to 1.6% and the FOS RED photometry is good to 2.0% when corrections for the focus change and FOS sensitivity degradation are included (described below). The dominant error in photometry is the location of the target in the aperture. Absolute calibrations for the four smaller apertures are computed from the set of transmission measurements relative to the 4.3″ aperture[7, 8]. PRISM spectra show a steep drop in sensitivity at the shortest and longest wavelengths.

Although the internal photometric repeatability of the FOS is ~1–2%, there are several effects that can systematically shift the photometric scale of an individual FOS spectrum (and for which you should correct where applicable). Table 16.3 summarizes the sources and levels of photometric errors. The photometric calibration of a typical FOS spectrum is accurate to ~5% for observations taken through the 4.3″ aperture but decreases to ~15% for observations taken through the smaller apertures and depends on the combination of grating, aperture, and detector used for the observation. These errors are described in more detail below.

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7. *FOS Instrument Science Report* 106 and 120.

8. The inverse sensitivity files delivered to PODPS and used in the pipeline processing 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 reference files were pre-launch estimates. As of March 1993, new reference files with sensitivity set to 1 have been delivered to PODPS for use with the uncalibrated apertures and any data calibrated with these files will remain in units of count rates and are not flux calibrated.

Table 16.3: FOS Photometric Errors

Source of Error	Level of Error	Comment
Decline in FOS sensitivity	~8% Blue ~5% Red	Depends on the grating and detector. New processing method will correct for this.
Miscentering target in aperture	~5%	Depends on target acquisition technique and aperture used. Error can be estimated fairly easily.
Change in telescope focus	5%	New processing method will correct for this.
Location of spectra	<3%	
Thermal breathing	~4%	
Jitter	<3%	
GIMP	<5%	
Offset in absolute spectrophotometric calibration system, i.e., difference between white dwarf model and HST standard star.	~6%	Depends on the wavelength and decreases with increasing wavelength. See Table 16.6.

Aperture Dilution Correction for Extended Sources

Flux calibrations are determined from observations of standard stars and compensate automatically for 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/sec^{-1}/cm^{-2}/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 16.4.
- Ω = Solid angle of the aperture in square arcseconds, e.g., 4.3″ x 1.4″ 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.[9]

Table 16.4: Recommended 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.

Sources of Photometric Errors

Below we describe briefly each of the sources of photometric errors and the steps you can take to overcome them, when possible. Described here are:

- Decline in FOS sensitivity.
- Miscentering.
- Flat fields.
- Change in telescope focus.
- Location of spectra.
- Thermal breathing.
- Jitter.
- GIMP.
- Calibration system offsets.

Decline in FOS Sensitivity

From early 1991 through mid-1992 the FOS has experienced a systematic decline in sensitivity for all gratings and detector combinations. This decline is not currently accounted for in the pipeline processing. 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.[10] The degradation has leveled off since mid 1992. In Figure 16.3

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

10. *FOS Instrument Science Report* 77.

we show the time dependence of the FOS sensitivity in a typical BLUE grating. Sensitivity changes for a typical RED grating is shown in Figure 16.4 and the G190H grating on the RED side in Figure 16.5.

Figure 16.3: Typical Time Dependence on BLUE Side

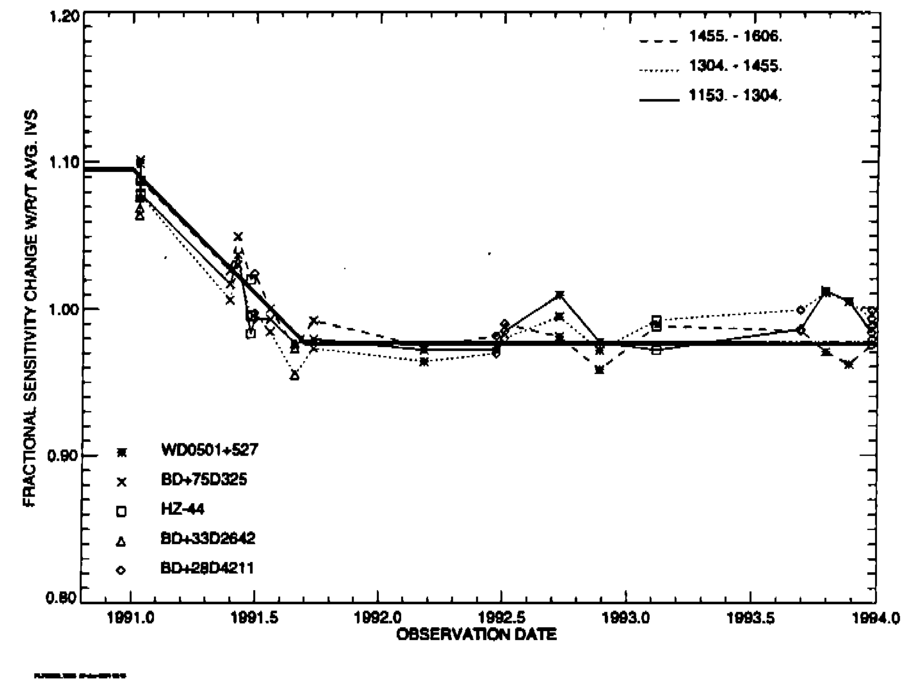


Figure 16.4: Typical Time Dependence on RED Side

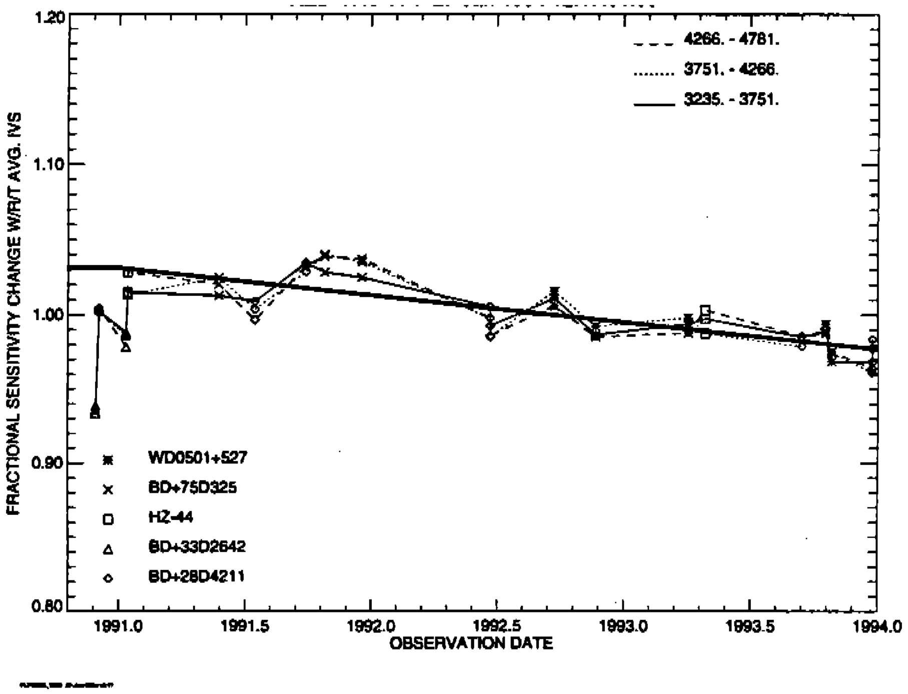
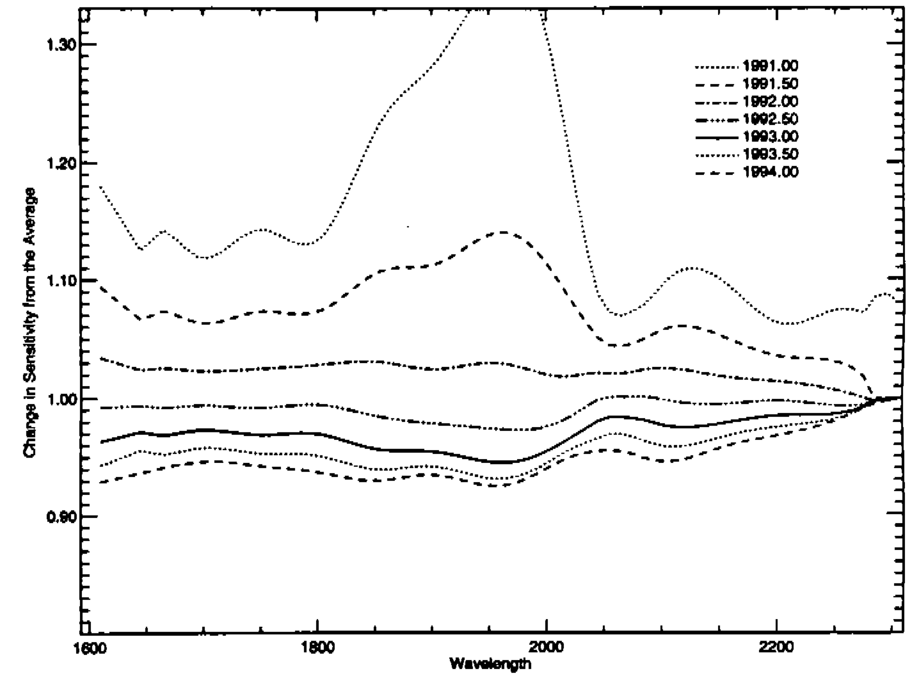


Figure 16.5: Time Dependence in G190H Grating on RED Side



Miscentering

The 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 systematically underestimated. 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[11] from the information supplied in Figure 16.6 and Table 16.5. Figures 16.6 a, b, and c show, for the circular 1", the circular 0.3", and the slit apertures respectively, the pre-COSTAR diminution of the transmitted flux from a point source versus the pointing error (miscentering). Table 16.5 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, <5% of the flux will be lost, while for observations utilizing a three stage peakup acquisition but taken through the 0.3" aperture roughly <10 to 17% 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.

11. See *Instrument Science Reports* 97 and 107.

Figure 16.6: Transmitted Flux Versus Pointing Error

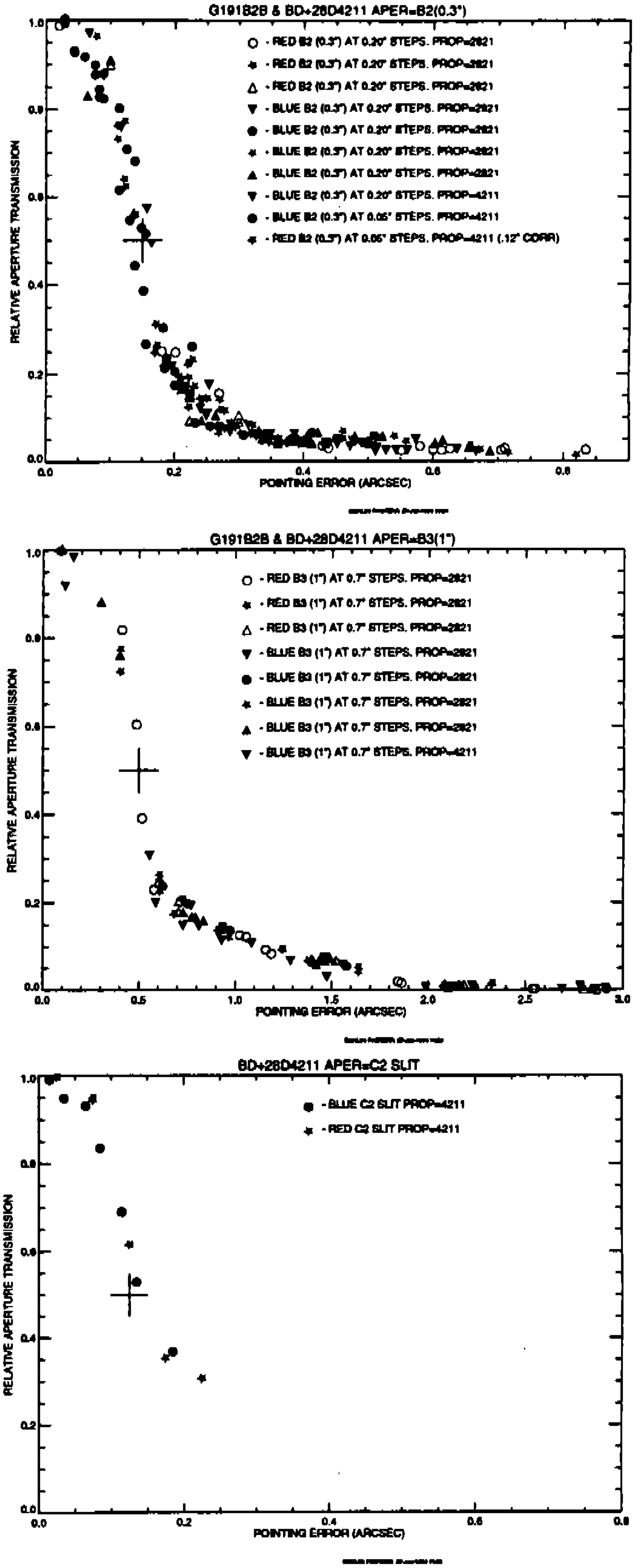


Table 16.5: Pointing Errors by Acquisition Method (Pre-COSTAR)

Acquisition Method	Maximum Pointing Uncertainty
Binary	0.15"
Standard 2 stage peakup (3x1 in the 4.3" and 2x6 with the 1.0")	0.49"
Standard 3 stage peakup (3x1 in the 4.3", 2x6 with the 1.0" and 3x3 with the 0.5")	0.21"
Standard 4 stage peakup (3x1 in the 4.3", 2x6 with the 1.0", 3x3 with the 0.5" and 5x5 with the 0.3")	0.04"

Flat-Field Correction

The FOS uses two stars (BD+28D421 and G191-B2B also called WD0501+527) to determine the flat field corrections for the various disperser and detector combinations. The overall flat field correction generally has an accuracy of better than 3%, but flats for certain specific dispersers and apertures and certain spectral regions can be substantially poorer. The so-called *superflats*, currently available only for the FOS blue detector, are generally the best flats. The red G190H flats have a dependence on aperture, time, and location on the photocathode (for details see papers by Keyes and Januzzi on flat fields in the *Proceedings of the HST Calibration Workshop*, J.C. Blades and S. Osmer, eds., November 1993). To a certain extent all flats are aperture dependent.

Good quality superflats[12] are now available for the blue side detector. Intensive investigations were conducted to determine the applicability of the different flat field reference files available to the pipeline calibration process for the blue detector. The recommendations for using the flat field files from these investigations are:

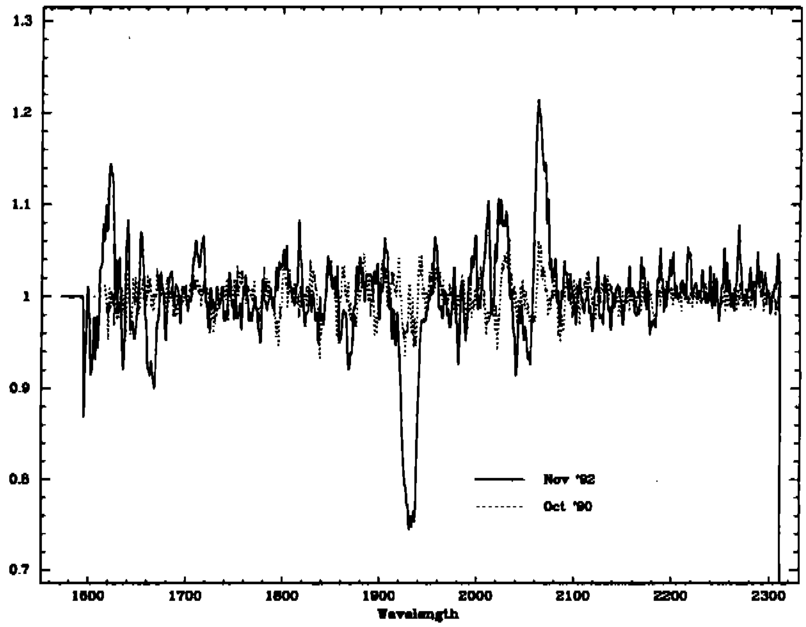
- For all FOS observations *before* January 1, 1992, with the SINGLE aperture and BLUE detector use the science verification (SV) 1.0" aperture flats.
- For observations *after* January 1 1992 use the new 4.3" aperture flats (superflats).
- The BLUE side data taken in a paired aperture during 1991 should 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.

The uncertainty in the flat fields for the blue detector is about 1%. However, the differences are occasionally as large as 2%.

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

The red side flats (especially G190H, G160L, and G270H) show significant wavelength structure (Figure 16.7). The flats also showed strong (>10%) wavelength dependent temporal variations during HST's first year of operation when the flat fields were not routinely monitored. Between January 1992 and June 1992, the G190H, G160L, and G270H FOS/RED flat fields were monitored monthly. During this intensive monitoring the flats varied by <2%. Since June 1992 the flats have been monitored about every 3 months. Several substantial (≥5%) new features appeared between June and November 1992. Since November 1992, changes have been <2%. Superflats were also generated for the red side, but these flats suffer from artifacts of the superflat analysis process called *ringing* and are not suitable for pipeline reduction. New FOS/RED superflat observations are under analysis and any updates will be announced widely and posted on STEIS. The present recommendation for the red side observations is to use the flat field available closest to the date of observation. The error in the flat fields for the red detector is approximately 2%. However, the differences are occasionally as large as 10%.

Figure 16.7: Red G190H Flat Field Reference Files



Red side observations should use the flat field closest to the observation date.

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

To understand the impact of the flat field used in the data reduction process for a particular observation, the target spectrum can be compared with standard star spectra and similar science observations taken as near in time as possible. Further, the flat used in calibration of the target spectrum should be compared with any other available flats for that instrumental configuration.[13] Figures 16.8 and 16.9 show the flat fields that are most commonly used for gratings for both FOS detectors.

Figure 16.8: Flat Field Reference Files for Blue High Dispersion Gratings

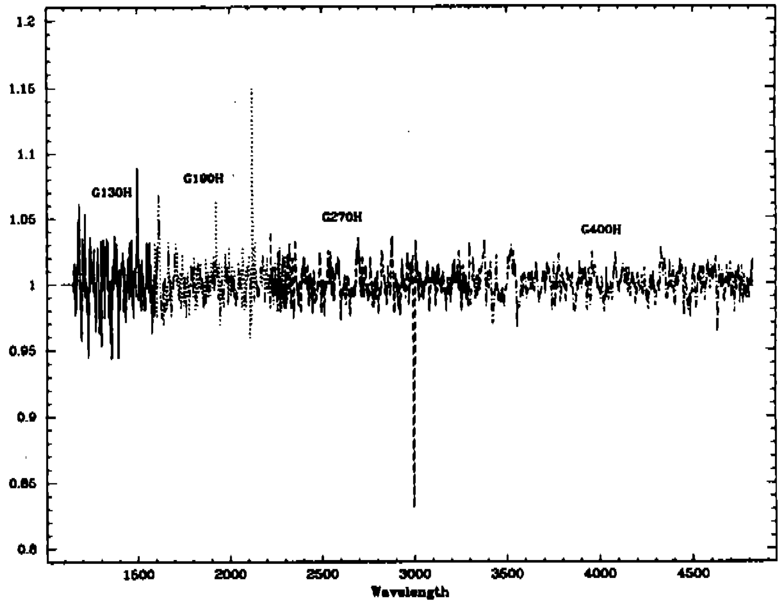
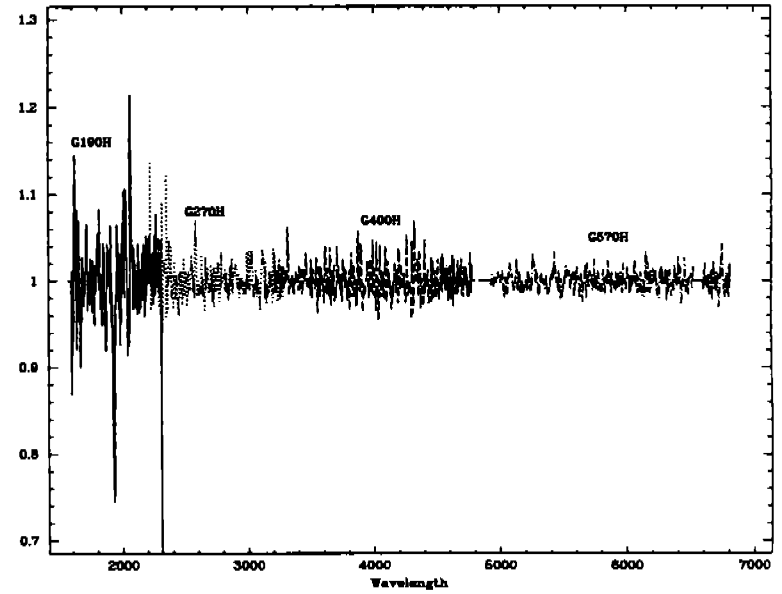


Figure 16.9: Flat Field Reference Files for Red High Dispersion Gratings



13. Information about flat fields is provided in *FOS Instrument Science Reports* 75, 78, 88, 89, and 90. Updates will be posted on STEIS.

Change in Telescope Focus

There has also been a systematic variation of FOS sensitivity 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.[14] The variations are such that a change in the focus by 15 microns leads to a photometric error of 8% in the 4.3 aperture. These variations also depend on the aperture and very slightly on wavelength. The typical photometric errors due to systematic change in focus are 5%.

Location of Spectra

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 a diode array are deflected on to the diode array. 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.[15] Furthermore, the shapes of the spectra on the photocathode are not linear and have a curvature of +/– 20 Y-base units because of small distortions in the magnetic fields of the Digicon detectors. This trend of the Y location of the spectrum and the curvature of the spectrum translates into a small internal miscentering (≤0.1") in the aperture. The effects of incorrect location of spectra are seen only for the 4.3" aperture and the 0.25"x 2.0" slit because parts of the point spread function could fall off the diode array. The photometric error due to incorrect estimation of the Y location of spectra is typically < 3% for the blue side and < 1% for the red side for observations obtained during the first 3 cycles of the HST. The largest errors in the calibrations are due to pointing error and not these internal errors, although the combination of Y-base errors plus small pointing errors can be disastrous.

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, and in turn changes the focus. This effect occurs on timescales equal to the orbital period of the

14. *FOS Instrument Science Report* 102.

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

spacecraft. The photometric error associated with thermal breathing is <4% and affects the flux in a random and uncorrectable way.

Jitter

Jitter is mostly due to the thermal instability of the solar panels and occurs when the spacecraft crosses the terminator and lasts 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 error depends on the aperture, and on the accuracy of centering the target in the aperture. The photometric error is rarely more than 1%, but always less than 3%.

GIMP

The GIMP correction is generally relevant only for data taken before April 5, 1993.

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 problem (GIMP) 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 GIMP. 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 GIMP (as long as the OFF_CORR switch is set to "PERFORM") in the creation of the calibrated spectral data (`.c0h` and `.c1h` files).[16]

The GIMP 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 GIMP. 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 over the edge of the array, creating 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 GIMP 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 GIMP correction is applied on a finer grid than what is provided by the pipeline GIMP correction and is applied in both the dispersion (X) and spatial (Y) axes. In the direction of the diode array the onboard GIMP correction is applied in units of 1/32 of the width of the diodes and in units of 1/32 of the diode height in the perpendicular direction. The onboard GIMP correction is calculated and updated every 30 seconds.[17]

Calibration System Offsets

This source of error in the FOS photometry is systematic and occurs due to uncertainty in the absolute spectrophotometric standard star fluxes in the UV. The pure hydrogen white dwarf model should be used in favor of the original HST fluxes of Bohlin et. al, 1990, that were transferred from the International Ultraviolet Explorer (IUE). This change in reference frame leads to a systematic difference in the absolute photometry of all UV FOS observations that is wavelength dependent. The difference between the white dwarf model and G191B2B is <15% for wavelengths <2000 Å, ~5% for the wavelength range 2000–3500 Å and <3% for wavelengths > 3500 Å (see Table 16.6). Preliminary comparison of the HST and model white dwarf absolute flux scales is shown in Figure 16.10. To convert to the white dwarf flux scale, divide the flux-calibrated data by the curve shown in Figure 16.10.

16. Prior to May 1991, **calfos** did not correct for GIMP. However, all data in the HST archive have been reprocessed after the GIMP 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 archives instead of using the data on your tape.

17. *FOS Science Instrument Report* 98.

Table 16.6: Uncertainty Introduced by Calibration System

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

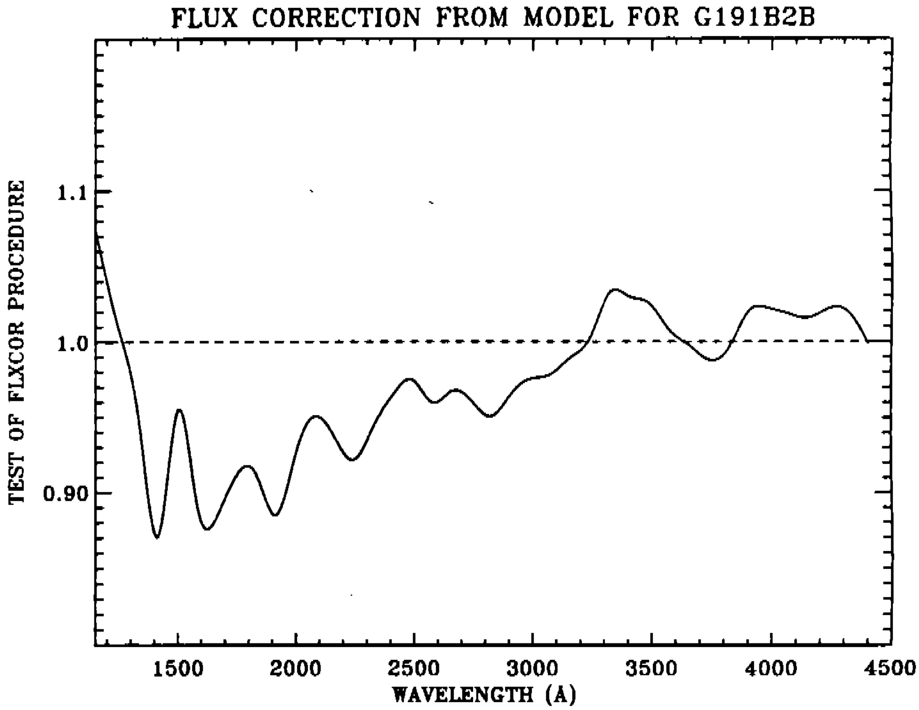


Figure 16.10: Ratio of HST to White Dwarf Flux Scales

Data Problems

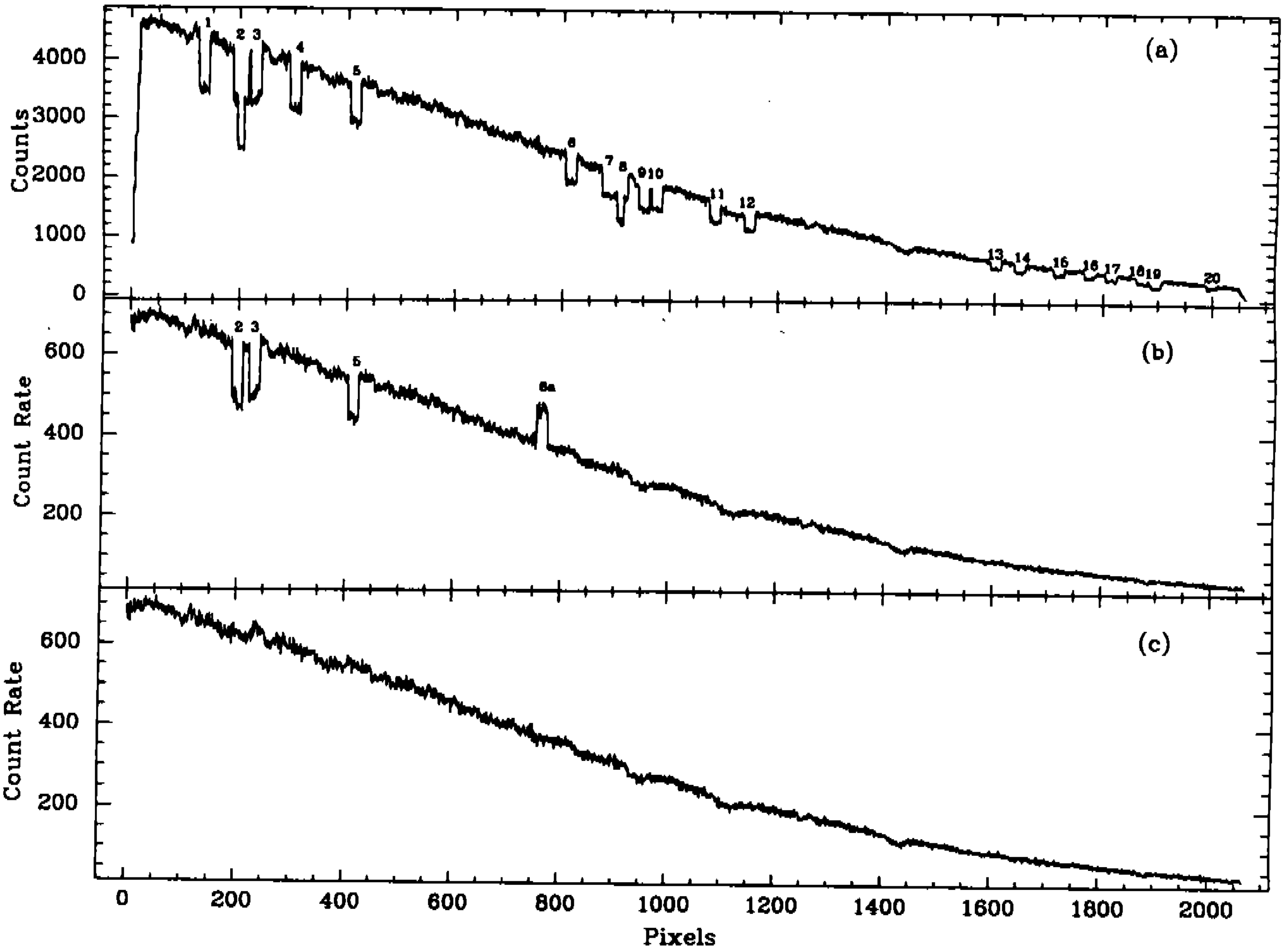
In this section we describe how to recognize and correct major problems that might affect your pipeline processed FOS data. The problems addressed here are:

- Effect of an incorrect dead diode reference file.
- Effect of a noisy diode.
- Effect of an incorrect flat field 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 the 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 269). 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 16.11) 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 16.11, 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 some 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.

Figure 16.11: Effect of Incorrect Diode Correction

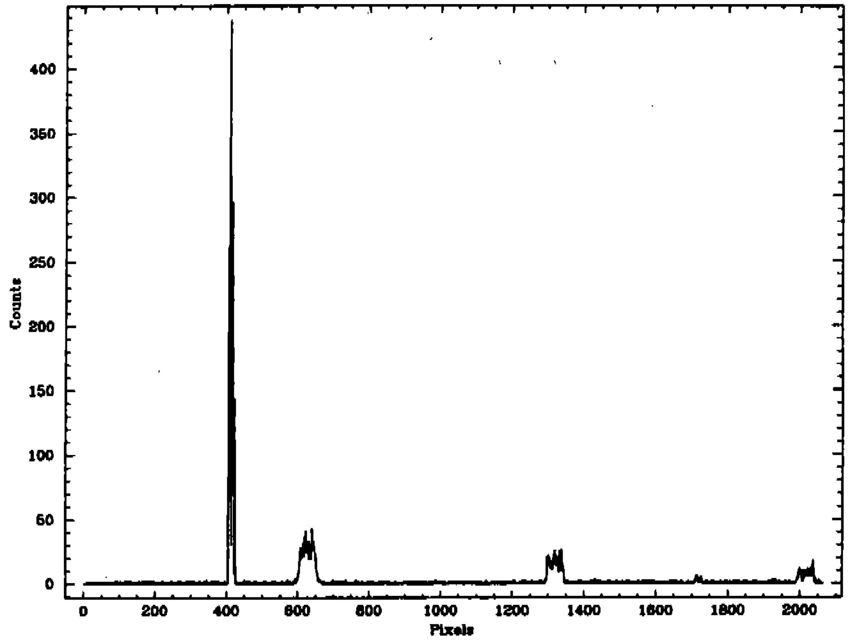


If you notice a feature in your data similar to the absorption feature described above, you should be suspicious that an incorrect dead diode reference file was used in the pipeline processing of your data. You can use the Calibration Reference screens in StarView to determine whether a more appropriate set of calibration reference files (including the dead diode reference file) now exist to calibrate your data (see "Identifying the Best Files Using StarView" on page 71). If so, you can retrieve those files and recalibrate your data using **calfos** (see "Recalibrating the Data" on page 75). 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 analysis@stsci.edu for further assistance.

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 16.12 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. STSDAS tasks to do this include **fixpix** or **splot** in its *etch-a-sketch* mode.

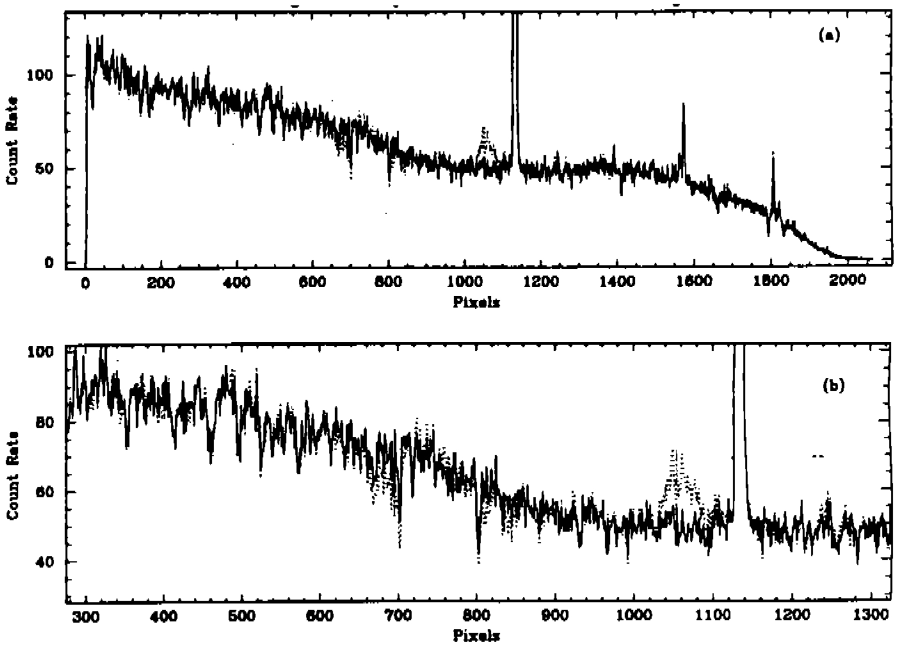
Figure 16.12: Effect of Noisy Diodes



Effect of Incorrect Flat Field 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 flat field. Small scale sensitivity variations result from both small scale inhomogeneities in the photocathode and diode-to-diode sensitivity variations. If an incorrect, or inappropriate, flat field reference file is used to flat field 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 flat fielding. Figure 16.13 shows an example of a spectrum that has been incorrectly flatfielded. Panel (a) shows the count rate data in the .c5h file that results from using both correct (solid line) and incorrect (dotted line) flat field files. Panel (b) shows a blowup of the region from 300 to 1300 pixels of the same data.

Figure 16.13: Incorrectly Flat-Fielded Spectrum of the Red G190H Grating



In general, the flat fields delivered by the pipeline should be accurate to 2–5%. However, there are a few detector and disperser combinations that show substantial time variations of their flat fields and that have not been adequately tracked by calibration observations. Table 16.7 gives a list of the detector and disperser combinations for which the flat field inaccuracy is known to be 5% or greater.

Table 16.7: Filter 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 are well advised to retrieve the flat field reference file used to calibrate their data from the HST archives (these have been delivered on the data tapes since May of 1993) and compare features in the calibrated spectrum with the flat field itself in order to confirm the reality of any weak features.

Delivered flat field reference files are produced from observations of stars made through large apertures. Observations obtained through smaller apertures indicate that the flat fields may be highly sensitive to the aperture used and there may be very small scale inhomogeneities in the photocathode that dominate the flat field response for small aperture observations. If you have observations obtained through an aperture smaller than 1", you may wish to retrieve flat field reference files obtained through one of the small apertures and try correcting your data with those flats to determine the importance of this effect for your observations. These will not be the recommended reference files and will not show up on the calibration reference screens in StarView. However they may be identified by looking at the listing of flat field reference files maintained on STEIS (see page 73).

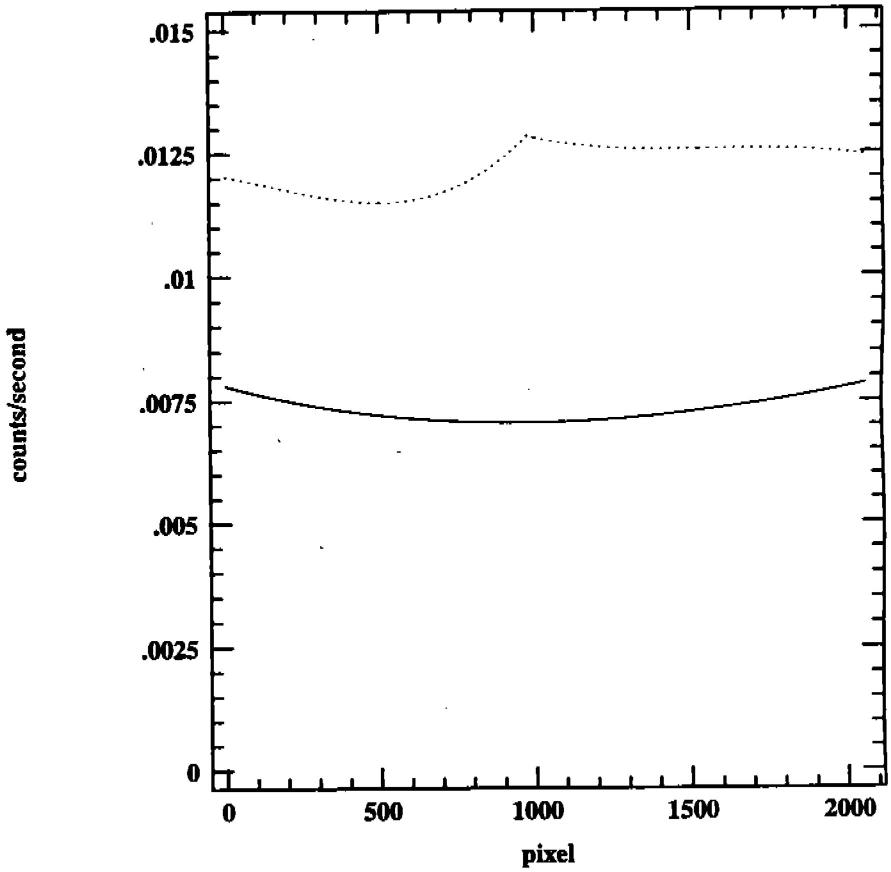
If you wish, you can also retrieve high signal-to-noise spectra from the HST archives that were taken near the time of your observation and in the same configuration as was used for your observations, to see if the same feature appears in these spectra.

Under-Subtraction of Background Light

The default reference background file used in **calfos** corrects for the dark signal from Cerenkov light. The background reference files are shown in Figure 16.14; 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* 71, 76, 79 and 80)[18]. 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.

18. A complete list of FOS Instrument Science Reports is provided on page 289.

Figure 16.14: 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[19] underestimates the background counts by approximately 12% at low geomagnetic latitudes and by about 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 new background reference file using a more sophisticated charged particle background and geomagnetic field model is being developed. Since this process will take some time, an interim solution is suggested: the current pipeline background spectrum (`.c7h` file) can be scaled by 30% (multiply `.c7h` by 0.3) and subtracted from the count rate file (`.c5h`) in order to subtract the remaining 30% of the background counts that were missed during pipeline processing. The resulting file can then be recalibrated accordingly, i.e., multiply the resulting image by the correct inverse sensitivity calibration file (IV*n*HFILE). An alternative approach is to make a local copy of the background reference image, scaled up by 30% (multiply by 1.3), modify the value of the BACKFILE header keyword in the raw data (`.d0h`) file (use the **hedit** task) to point to this new reference image, and then recalibrate the dataset using the **calfos** task in STSDAS.

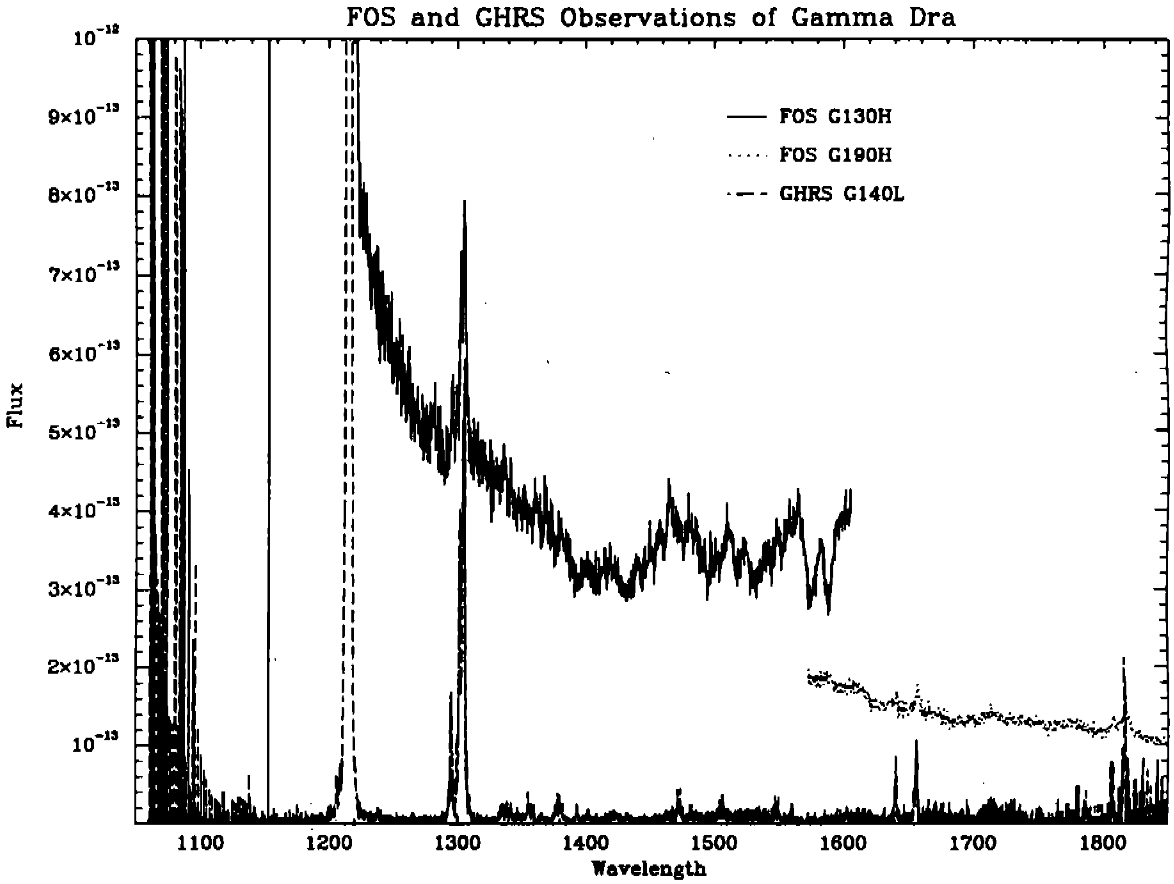
19. *FOS Instrument Science Reports* 99 and 114.

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

Scattered light in the FOS is probably caused by scattering off the grating. Pre-flight data taken in the laboratory shows 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 16.15). 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 of a problem.

Figure 16.15: Scattered Light Comparison of GHRS and FOS



A full correction for scattered light requires an understanding of the source of the scattering, and the path taken by the scattered light (i.e., is it diffracted or merely reflected onto the photocathode?) in order to properly model the wavelength dependence of the scattered light and its dependence on the incident spectrum. Such a correction and understanding is not currently available. A complete investigation is underway to investigate the possible characterization of scattered light. The FOS pipeline reduction does not currently account for scattered light.

An interim solution[20] is recommended to correct for scattered light in those gratings which have diode regions with no sensitivity to dispersed light. These unilluminated portions of the spectrum directly measure the scattered light component for each individual observation. The average number of counts in the region with no sensitivity (see Table 16.8) provide a more accurate measure of the scattered light. Subtract the average number of counts from the .c5h file, and recalibrate. For the blue side G190H grating and solar type spectra the same technique can be used by determining the average counts to be subtracted from the 1500–1700 Å region in which there is

20. *FOS Instrument Science Reports* 103 and 114.

effectively no intrinsic light from the source. Since background counts are known to be wavelength dependent, correction for pipeline undersubtraction of the background (see "Under-Subtraction of Background Light" on page 238) should be done first, before correcting for scattered light in this way. This procedure does not address the complex issue of wavelength dependence of the scattered light, nor does it allow correction for scattered light for the gratings that do not have a region of no sensitivity. Table 16.8 lists the minimum and maximum pixel numbers that can be used for gratings that have regions of no sensitivity. The values listed apply to spectra with FCHNL=0, NCHNLS=512, NXSTEPS=4, and OVERSCAN=5.

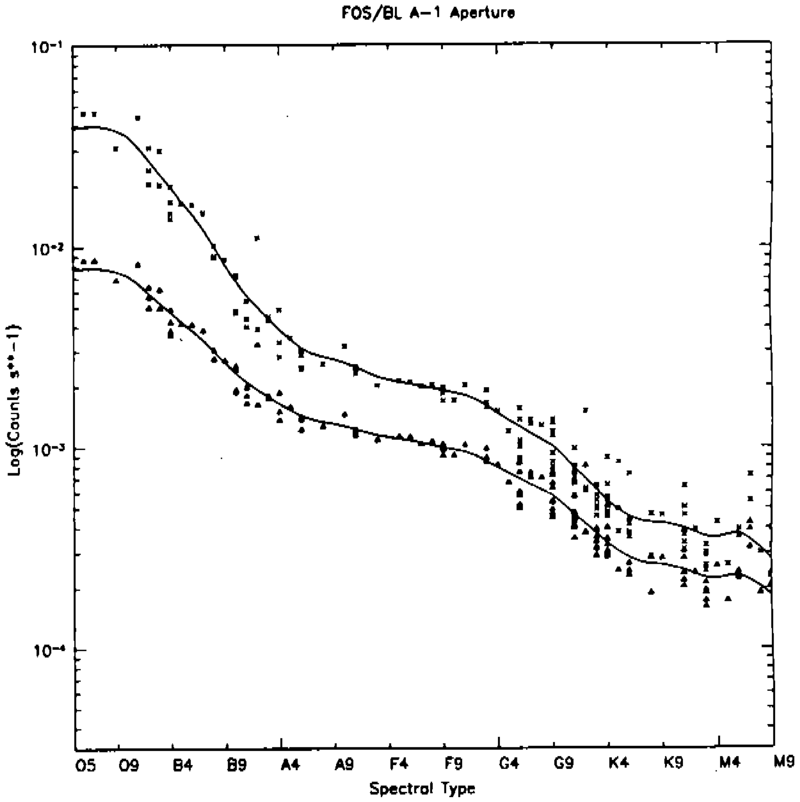
Table 16.8: Regions to be Used for Scattered Light Subtraction

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

The amount of scattered light depends on the spectral energy distribution of the object being observed and the sensitivity of the detector. For cool objects the number of scattered light photons can dominate the dispersed spectrum in the UV.

For observations obtained using gratings that do *not* produce spectra with unilluminated portions, there is no straightforward and reliable way to correct for the scattered light. You can assess whether scattered light is likely to be a significant contaminant in your spectrum using the information provided in Figure 16.16 as a rough guide. Figure 16.16 shows a plot of the *predicted* scattered light countrate for a range of stellar spectral types, scaled to a V magnitude of 15. These predictions were calculated under the simple assumption that the scattering itself is reflective and wavelength independent. In this model, the scattered counts can be approximated as a single scale factor which is empirically calculated. The count rate in the .c5h file can be compared with the predicted count rate from Figure 16.16 (scaling from V_{mag}=15 to the V_{mag} of your source), in order to determine whether the spectrum is likely to be seriously contaminated by scattered light. The two solid lines in the figure represent $E(B-V)=0$ and $E(B-V)=0..5$.

Figure 16.16: Predicted Scattered Light Count Rates



17 FOS Details

In This Chapter...

This chapter[1] will describe in detail both the FOS target acquisition and data acquisition modes. It then explains some of the more important header keywords and defines a number of terms used in working with the FOS. The last section of this chapter explains how the steps in the PODPS pipeline calibration are performed.

Data Acquisition with the FOS

Target Acquisition Modes

Although 70% of the blind pointings with the HST fall with in 1″ of the FOS science aperture center[2], an onboard target acquisition is still required with the FOS to center the target into the small FOS apertures. The targets are acquired in several different modes depending on the nature of the target. The different modes and the nature of the target acquisition data files are described below. These target acquisition files provide important information concerning the location of the target in the aperture. The target acquisition data file is usually the first file in a given observation set. The OPMODE

1. This chapter was written by Anuradha Koratkar of the Science Instrument Branch at STScI.

2. Figure 2.1.0 in the *FOS Instrument Handbook*, version 4.0

associated with each target acquisition type is given at the beginning of each description. The different modes and their associated OPMODE values are:

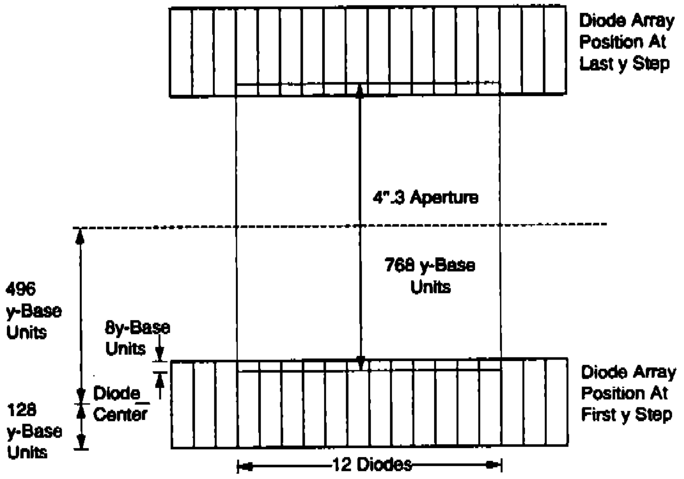
- Imaging target acquisition mode: ACQ
- Binary search acquisition mode: ACQ/BIN
- Peak-Up or Peak-Down: ACQ/PEAK
- Firmware target acquisition mode: ACQ/FIRMWARE

Imaging Target Acquisition

When imaging target acquisition mode is used, the OPMODE values are ACQ or IMAGE. This acquisition mode is typically used for EARLY acquisition, INTeractive ACQuisition, or to obtain a verification image of the FOS large aperture to check the target position in the aperture.

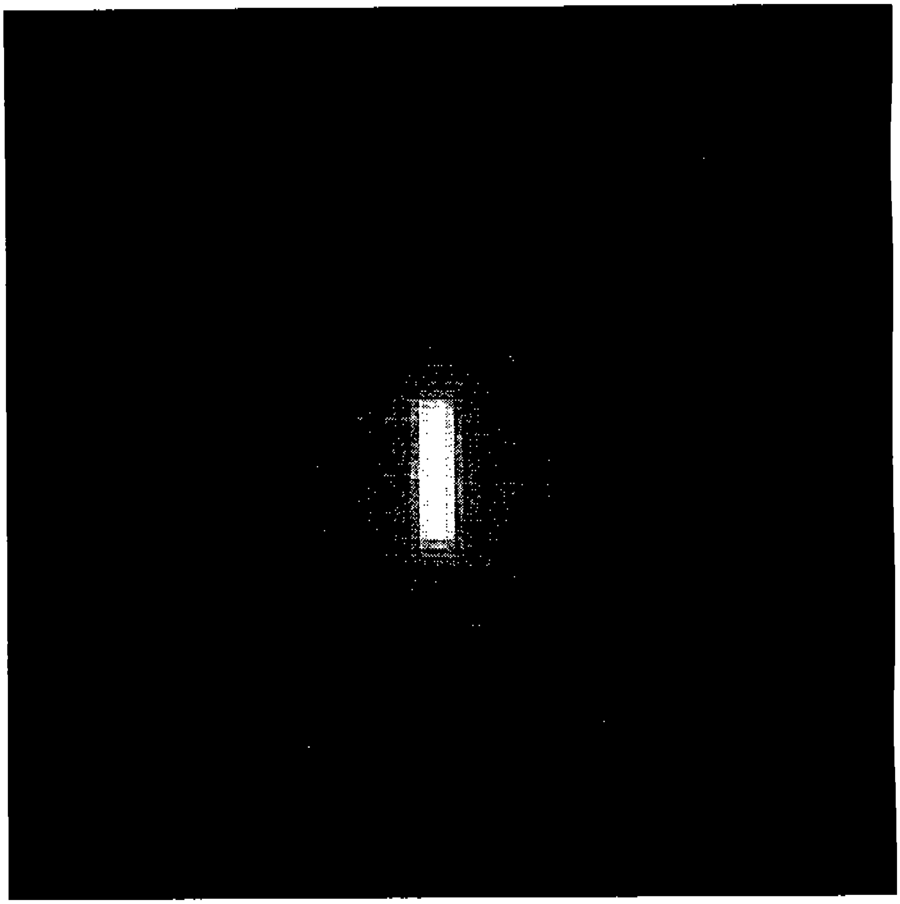
In a standard ACQ image the FOS Digicon is commanded through a sequence of X-steps and Y-steps which map the aperture. The 4.3" aperture is scanned with 64 strips, each of which is the height of the diode array, beginning at the bottom edge of the aperture. The distance between the strips is 0.08958" (16 Y base units). Each scan reads out 20 diodes with the central 12 diodes spanning the 4.3" aperture. In the standard mode (NXSTEPS=4 and OVERSCAN=5) the number of pixels in each strip is 96. Thus the image has 96 x 64 pixels where each pixel is 0.08958" x 0.08958" on the sky (see Figure 17.1). The calibrated (i.e., output from **calfos**) data files have 64 groups with each group having 96 pixels. The raw data file (`.d0h`) is an actual 96x64 image (1 group) file.

Figure 17.1: Digicon Faceplate Sampling Pattern in a Target Acquisition Image



The substepping in both the X and Y directions, and the elongated shape of the diodes, blurs and stretches the image (see Figure 17.2). A point source (which has the size of a PSF) on the photocathode is recorded by the same diode for 4 consecutive pixels in the X direction and 16 consecutive pixels in the Y direction. The **tarestore** task in STSDAS can be used to deconvolve the image. In this task the image is trimmed and the flux resampled in the pixels. The **modeone** task also uses the **tarestore** task and displays the deconvolved image with the correct orientation on the sky (north and east are indicated).

Figure 17.2: Sample FOS Target Acquisition Image



The position of the target in the image can be found by using the task **aperlocy** in STSDAS. This task computes the location of the image edges, the midpoint of each axis, the centroid of the image, and the total flux in the image. The output of this task is in diodes for the X-axis and Y-base units for the Y-axis. This task also takes into account the elongated shape of the diodes in determining the target centroid in the aperture. The nominal center for the 4.3" aperture is at the pixel (48,32). To determine the nominal aperture center in diode and Y-base units, the following equations are used:

$$\text{aper\_center (X)} = \text{FCHNL} + \frac{(48-1)}{\text{NXSTEPS}}$$

$$\text{aper\_center (Y)} = \text{YBASE} + (32-1) \times 16$$

where:

- FCHNL is the first channel.
- NXSTEPS is the number of substeps.
- YBASE is the location of the diode array for the first group.

The centroid of the target can then be compared with the aperture center to determine the location of the target in the aperture. Note that the **aperlocy** task can also be used for images of the paired apertures. See the on-line help files in STSDAS for details.

Binary Search Acquisition

Binary search acquisition mode is indicated by an OPMODE value of ACQ/BIN. This acquisition method is used for targets that are point sources with well known energy distributions. Although ACQ/BIN is designed to select the *n*th brightest object in a crowded field, this option has not been used so far. Hence, the following discussion will describe how the brightest star is acquired.

If a binary search is successful, we can only determine the amount of telescope slew that occurred to place the target at the nominal position on the array, but cannot locate the exact position of the target in the aperture unless a confirming image has been acquired after the acquisition. The nominal centering of the binary search places the target 70% of the time within +/– 0.15" to +/– 0.2" of the nominal target center, depending on the number of counts in the acquisition peaks.[3] The slew conducted to place the target at the center of the 4.3" aperture can be found in the .shh file. The FOS X and Y slews are the 894th and 896th words in the last group of the .shh file (use the **listpix** task in STSDAS). To convert the numbers obtained by **listpix** into arcseconds, multiply them by 2.25e–4. Throughout this discussion we will use the FOS coordinate frame. Please refer to "Converting X,Y Coordinate to Spacecraft V2,V3" on page 266 for information about converting from the FOS X,Y coordinates to the V2,V3 coordinate frame as projected on the sky.

3. As derived from simulation of the binary search.

The binary search algorithm begins by mapping the 4.3″ aperture (only the 12 central diodes which cover the 4.3″ aperture provide the data although 16 diodes are read out) with 3 Y-scans which are stored in the raw data file as 3 groups. The first scan (i.e., group 1) is of the central region of the 4.3″ aperture, the second scan (group 2) is of the lower region of the 4.3″ aperture, and the third scan (group 3) is of the upper region of the 4.3″ aperture. The binary search acquisition program then compares the count rates in the three scans, and locates the target in one of the three scans by finding the total number of peaks in the scan and the number of counts in each individual peak. The brightest peak, representing the target, is then selected. If more than five peaks per scan are found by the binary search algorithm, the target acquisition fails. If there are two peaks (within a diode width) in two adjacent scans, the algorithm sums up the number of counts in the two peaks to determine the brightness of the target. The search program then continues (up to 8 more tries) to deflect the target (in the Y direction) until the target is on the edge of the diode array, i.e., until the number of counts in the peak is half the maximum number of counts observed in the initial three scans. For each deflection the data are scanned and stored as a group. If the target acquisition is successful the telescope slews to the position on the array and the science observations are conducted. The binary search could fail due to one of the following reasons:

- The algorithm was not completed in 11 steps because the target was extended, or it had a flat energy distribution, or the GIMP moved the target (for observations when onboard GIMP was not yet activated).
- The field was too crowded, i.e., the algorithm found more than five peaks in a scan.
- The source was much fainter than determined by the observer, i.e., there were very few counts in the observations.
- The faint limit provided by the observer was too high, i.e., the algorithm encountered fewer counts than the faint limit.
- The bright limit provided by the observer was too low, i.e., the algorithm encountered too many counts.
- The faint limit provided by the observer was too low, i.e., the algorithm was confused due to the dominance of the wings of the PSF.

If the binary acquisition fails, the telescope *does not slew* to place the target at the nominal center of the 4.3″ aperture, and the object is observed at the current pointing position of the telescope. In some of the types of failures mentioned above, we can estimate the location of the target in the 4.3″ aperture. This information may be used to determine the photometric error in the following science observations, if there was any flux detected during these observations.

The ACQ/BIN data (`.d0h` file) has up to 11 groups (depending at which stage the algorithm stopped the search) and each group has 64 pixels (12 diodes scanned with NXSTEPS=4 and OVERSCAN=5). If there are less than 4 groups, the binary search target acquisition has failed. The pipeline calibration just corrects the data for paired-pulse effects (see "Pipeline

Calibration of FOS Data" on page 267) and converts the raw counts into a count rate. No further calibration procedures are applied.

The location of the target in the FOS X,Y coordinate system in the last step of a successful binary search can be determined as follows. The location of the diode array, the Y coordinate in units of Y-bases, for each scan can be found by searching the header keyword YPOS in the group parameter block of the `.d0h` file (use the **grlist** task in STSDAS to generate a list file of each group in the `.d0h` file and then find the value of the header keyword YPOS using **hedit**). If the target acquisition has been successful, the YPOS of the last scan corresponds to the position which places the target on the edge of the diode array. The X, Y coordinates of the target are given by

- Y_{target} = YPOS of the last scan + 128 (half the diode height), if the target was found initially in groups 1 or 3.
- Y_{target} = YPOS of the last scan – 128, if the target was found in group 2.
- X_{target} = The centroid of the 9 pixels around the peak in the last group after mean subtraction.

The slews in the X and Y directions necessary to move the target to the nominal center of the 4.3″ aperture are determined as follows:

- $Y_{slew} = Y_{target}$ – YPOS of the first group.
- $X_{slew} = X_{target} - 32$ (the central pixel of the scan).

The X,Y coordinates have units of pixels and Y-bases respectively. The slew can be converted to arcsec using the conversion factor that one diode=4 pixels=0.357″ and 256 Y-bases = 1.43″ for pre-COSTAR observations.

If you need to determine the nature of the binary search acquisition failure and the relocation of the target in the aperture, you should contact the data analysis staff at STScI by sending e-mail to analysis@stsci.edu, to run the FOS binary search acquisition simulator. This simulator uses the `.d0h` file and recreates the acquisition strategy. For binary search failures due to incorrect brightness limits, one can redefine the limits in the simulation and then determine the location of the target in the aperture. For binary search acquisition failures due to low number of counts or a crowded field, target location can not be estimated. For a binary search failure due to overrun in the number of steps the location of a target in the aperture may be accurately determined.

Peak-up or Peak-Down

The *peak-up* or *peak-down* mode is identified by the OPMODE value of ACQ/PEAK. This acquisition mode is used for bright targets, variable targets, or targets whose energy distribution is not well known. This acquisition mode has been used very often in the first three cycles.

The *expected* pointing accuracy of the ACQ/PEAK acquisition depends on the pattern used to acquire the target for pre-COSTAR observations. In a standard 2-stage peak-up which used the 4.3″ and 1.0″ apertures the expected pointing uncertainty is 0.35″. In a standard 3-stage peak-up using the 4.3″, 1.0″ and 0.5″ apertures the expected pointing uncertainty is 0.17″. In a standard fine peak-up with four stages using the 4.3″, 1.0″, 0.5″ and slit apertures the expected pointing uncertainty is 0.03″ in the X direction. (Note that the Y uncertainty for this acquisition is 0.17″). In a standard fine peak-up with four stages using the 4.3″, 1.0″ apertures, and 0.3″ aperture twice, the pointing uncertainty is 0.03″. In general, the pointing accuracy is determined by the SCAN-STEP-X and SCAN-STEP-Y parameters of the search pattern. The *maximum* expected error is 0.7 times the scan step size for a standard acquisition pattern with a circular aperture.

All of the accuracy estimates in the previous paragraph are for *pre-COSTAR* observations.

The ACQ/PEAK algorithm uses a pre-loaded step and integrate pattern. Usually the algorithm begins with three dwell points in the Y direction which image the 4.3″ aperture. The three scans from the dwell points are stored in the raw data file as three groups. The dwell point with the maximum number of counts is determined and the telescope is positioned with the center of the aperture corresponding to this dwell point. Next a smaller aperture and a pattern chosen by the observer is used and the process is repeated. Each scan from this acquisition step is stored as a group in a separate data file. Hence, each stage of the ACQ/PEAK has its own individual file numbered sequentially. For example, a standard 3-stage peak-up will have three files, the first file containing the three groups corresponding to the three scans obtained with the 4.3″ aperture, the second file containing 12 groups corresponding to the 12 scans obtained with the 1.0″ aperture, and the third file containing nine groups corresponding to the nine scans obtained with the 0.5″ aperture. If each group is plotted as a function of its location, the position of the target in the aperture can be determined with reasonable accuracy. The collage of scans also provides a crude image of the surface brightness of the object. A task to do this is in preparation (STSDAS tool **makeapicture**). For additional details, contact the data analysis staff at STScI (analysis@stsci.edu).

Firmware Target Acquisition

The firmware target acquisition mode is identified by the OPMODE value of ACQ/FIRMWARE. Firmware mode is occasionally used for planetary observations, although this is an engineering mode. This mode sometimes fails because the brightness limits have not been set accurately by the observer.

The ACQ/FIRMWARE mode maps the 4.3" aperture with a certain number (*m*) of Y steps acquiring data from 20 diodes covering the aperture in the standard ACCUM mode. The target acquisition data therefore has *m* groups with 96 pixels (NXSTEPS=4 and OVERSCAN=5). The microprocessor onboard the FOS searches for the peaks in the data array within a specific window and the target is centered at this location. The *m* groups can be plotted as a function of location and the position of the target in the aperture can be determined similar to the ACQ mode.

Data Acquisition Modes

The FOS data acquisition mode depends on the scan pattern used to acquire the data. The OPMODE and GRNDMODE 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
- ***Spectropolarimetry***: OPMODE=ACCUM, GRNDMODE= SPECTROPOLARIMETRY
- ***Time-resolved spectrophotometry***: OPMODE=PERIOD, GRNDMODE=TIME RESOLVED
- ***Rapid readout***: OPMODE=RAPID, GRNDMODE=RAPID READOUT

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 FOS acquires data using a pattern of magnetic deflections of the spectrum along the dispersion direction. The two techniques used to generate the pattern are called *substepping* (NXSTEPS) and *overscanning* (OVERSCAN), see also "Substepping and Overscanning" on page 216. For the standard ACCUM mode, the default value of NXSTEPS is 4 and OVERSCAN is 5. Each pixel in the spectrum, except for the pixels at the edges, has contributions from 5 diodes if OVERSCAN=5. 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:

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

ACCUM mode spectra with 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 two minutes for the red detector and 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.

Raw paired aperture data are stored as concatenated data per group, i.e., data from aperture A and B are stored in one group in the raw data files, similar to spectropolarimetry data for each pass direction.

Spectropolarimetry Mode

Spectropolarimetry mode[4] 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 at a given waveplate angle, which are alternately deflected onto the diode array and 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 multiples 4, 8, or 16 depending on the number of polscans requested. The group contents of the raw (.d0h) data file are shown in Table 17.1. Note that the number of pixels in each group is twice the number of pixels in a 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 is a bit different than the raw data files 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

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

are stored in 2 x POLSCAN number of groups, similar to the wavelengths. Note that for polarimetry data the statistical errors cannot be simply combined. The errors in the Stokes parameters are calculated by the data reduction pipeline separately. The polarimetry-specific data is stored once again as groups in a separate file.[5]

Table 17.1: 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 data set 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 data set 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 only from 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` data set (see below) and so is more conveniently obtained from there.

The `.c2h` file is a data set 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

5. See *FOS Instrument Science Report* #078.

data set, this data set 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 data set 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 data set.

The group organization of the .c0h, .c1h, .c2h, and .cqh files is shown in Table 17.2.

Table 17.2: Group Organization of the Calibrated .c0h, .c1h, .c2h, and .c1h 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 data set with 56 groups containing the reduced polarimetry data. The data set 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 17.3.

Table 17.3: 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

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.

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).

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 that, 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 "Pipeline Calibration of FOS Data" on page 267 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 17.4.

Table 17.4: 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 present in the PERIOD mode. 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 much shorter intervals 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 (summed in quadrature). The `.c3h` files effectively provide the light curve of the target for the length of the observation. See "Pipeline Calibration of FOS Data" on page 267 for more details on special mode processing.

Deriving Information About Your Observation

Headers and Keywords

The 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. The description of each keyword is often provided in the header itself. Table 17.5 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 (see "Header Keywords" on page 22). Table 17.6 lists some of the important header keywords used to interpret FOS data.

Table 17.5: 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 GIMP 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 GIMP 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

Keyword Type	Information in Keywords	Source
Calibration Keywords	Observing time, user-supplied GIMP 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
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, i.e., 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 17.6: 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.
GRNDMODE	Ground software mode of FOS. Can be SPECTROSCOPY, ACQ, 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. Hxx means GxxOH filter, L15 means G160L, L65 means G650L, and PRI means PRISM
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 acquision and other specific modes, see below).

Keyword	Description and Comments
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 angstroms. (Not populated in .c0h file).
MAXWAVE	Maximum wavelength in angstroms. (Not populated in .c0h file).
YFGIMPEN	Onboard GIMP 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, rounded off to the nearest 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.
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.

Definitions

The following definitions are provided to help explain some of the details of data acquisition.

- *INTS:* This parameter indicates the number of repetitions of the livetime/deadtime cycle, whereby electrons are counted in the selected diode accumulators with no change in the magnetic deflection. Changing INTS provides a means for altering the amount of time data are collected at a given deflection value while keeping the livetime short so that as little good data as possible are rejected. The header keyword is INTS.
- *SUBSTEPS:* This parameter indicates the number of magnetic field deflections of the photo-electrons in the dispersion direction. The default value is 4 (quarter stepping). The data go into new memory locations with each substep. The corresponding header keyword is NXSTEPS.
- *OVERSCAN:* This parameter is the number of times to add information into the memory array, with an offset of one memory location at each overscan. Each offset is accompanied by a magnetic deflection of the spectrum in the dispersion direction so that a photon from a given X-location (λ) on the photocathode falls into the adjacent diode, which is then summed into the same memory location for all overscan steps. The default value of this parameter is 5. The purpose of overscanning is to average out the response of the different diodes, including dead diodes. The header keyword is OVERSCAN.
- *YSTEPS:* This parameter indicates the number of magnetic deflections of the electrons in the direction perpendicular to the dispersion. This parameter is used to map the photocathode (IMAGE mode), to switch between the two spectra produced by the polarizer, or to acquire either of the paired apertures. In standard ACCUM mode this parameter has the default value of 1. The header keyword is YSTEPS.
- *SLICES/BINS:* A slice consists of an entire deflection sequence. Data from each slice goes to a new memory location. This is used for time resolved spectrophotometry. The header keyword is SLICE.
- *PATTERN:* This is a complete series of slices. Counts in subsequent patterns are added to the corresponding previous values in the data array. The header keyword NPAT determines the number of times a pattern should be executed to achieve the exposure time.
- *READOUT:* This consists of sending the science data to the CU/SDF for either storage on the tape recorder or for telemetry to the ground. FOS readouts are non-destructive and are performed at regular intervals (~4 min for the blue detector and ~2 min for the red detector) without memory clears in order to protect against loss of data. The last readout contains all the data accumulated since the previous memory

clear. In the standard ACCUM mode each readout is stored as a separate group in the data files. The header keyword NREAD gives the number of readouts per memory clear.

- ***Memory Clears:*** A memory clear sets to zero all locations in the science data array to allow input of new data. The number of times that a memory clear is repeated in a given observation is given in the NMCLEARS keyword.

Calculating Exposure Times

This section explains how to calculate exposure times using values from header keywords. The different times in the FOS headers are:

- ***LIVETIME:*** The fundamental unit of integration time, and is the time between opening and closing the 512 accumulators. The shortest time is 3 ms. The header keyword is LIVETIME.
- ***DEADTIME:*** Time required for housekeeping chores. It is normally 10ms. The header keyword is DEADTIME.
- ***Exposure time per pixel:*** This is the integration time per pixel that contributes to the counts observed in that pixel. This differs from the exposure time per spectrum because of substepping. The header keyword EXPOSURE gives the total exposure time for a pixel in seconds.
- ***Exposure time per group:*** This is the integration time for a given group, which is equivalent to the integration time per diode. The exposure time of the group (exp_{group}) (units of seconds) using the header keywords is determined as follows:

$$exp_{group} = \text{EXPOSURE} \times \text{NXSTEPS}$$

This simple equation in terms of the basic FOS time and data acquisition terms is given by:

$$exp_{group} = \text{LIVETIME} \times 7.8125\text{E-6} \times \text{INTS} \times \text{NXSTEPS} \times \text{OVERSCAN} \times \text{YSTEPS} \times \text{NPAT}$$

In this calculation we have not accounted for the deadtime because we are interested in calculating only the time over which the photons were collected.

- ***Elapsed time per group:*** This is the time between two groups. It is longer than the exposure time of a group because of the added deadtime. The following equation can be used to determine the elapsed time of a group for nearly all observations.

$$elapsed\ time_{group} = (\text{LIVETIME} + \text{DEADTIME}) \times 7.8125\text{E-}6 \times \text{INTS} \times \text{NXSTEPS} \times \text{OVERSCAN} \times \text{YSTEPS} \times \text{SLICES} \times \text{NPAT}$$

This elapsed time can be used to determine the start and stop time of each group in the data. The procedure is as follows:
The FPKTTIME in the group parameters of the .d0h file is the time at which the integration for that group was stopped. In the headers this time is given (to the accuracy we can measure) in units of modified Julian date, which is the Julian date minus 2400000.5. This time can be converted from modified Julian date to the standard notation using the **epoch** task. The time at which the integration was started is given by:

$$start\ time = \text{FPKTTIME}_{group} - elapsed\ time_{group}$$

The group parameters can be determined by running the task **grlist** to determine all the groups in the d0h file and then finding the value of the necessary keyword using **hedit**. Note that the FPKTTIME is accurate only to 1/8 second.

- ***Exposure time for the observation***: This is the total time during which the FOS accumulated data for the observation and is given in the header keyword EXPTIME. This should be the exposure time given by the GO in Phase II instructions. This is given by the equation:

$$exp_{total} = \text{EXPOSURE} \times \text{NXSTEPS} \times \text{NREADS} \times \text{NMCLEARS}$$

In the basic FOS data acquisition units, this is:

$$exp_{total} = \text{LIVETIME} \times 7.8125\text{E-}6 \times \text{INTS} \times \text{NXSTEPS} \times \text{OVERSCAN} \times \text{YSTEPS} \times \text{NPAT} \times \text{SLICES} \times \text{NREAD} \times \text{NMCLEARS}$$

- ***Elapsed time for the observation:*** This is the total time spent by the FOS for a given observation, which includes the deadtime during which photons were not accumulated. Corresponding to the exposure time for the observation is the elapsed time for the observation. This is given by

$$elapsed\ time_{observation} = (\text{LIVETIME} + \text{DEADTIME}) \times 7.8125\text{E-}6 \times \text{INTS} \times \text{NXSTEPS} \times \text{OVERSCAN} \times \text{YSTEPS} \times \text{NPAT} \times \text{SLICES} \times \text{NREAD} \times \text{NMCLEARS}$$

Converting X,Y Coordinate to Spacecraft V2,V3

Occasionally, you may want to convert from the FOS X,Y reference frame to the telescope's reference frame. The FOS X,Y coordinate system is such that the X axis is parallel to the diode array and the Y axis is perpendicular to the diode array with positive going from bottom to top. Further, the X,Y coordinate frame is rotated with respect to the telescope's V2V3 coordinate frame. Figures 17.3 and 17.4 show the coordinate axes for both detectors before COSTAR was installed.

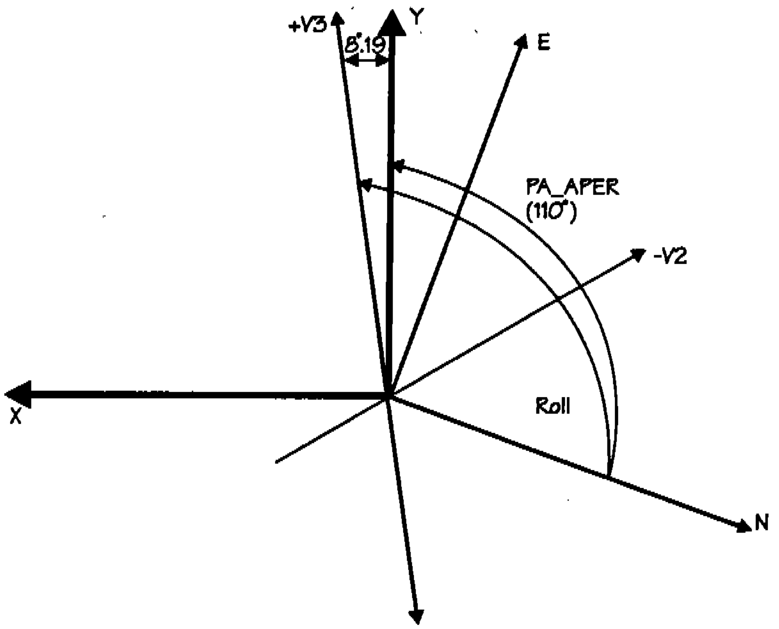


Figure 17.3: Orientation of BLUE Side, PA_APER=110° in this Example

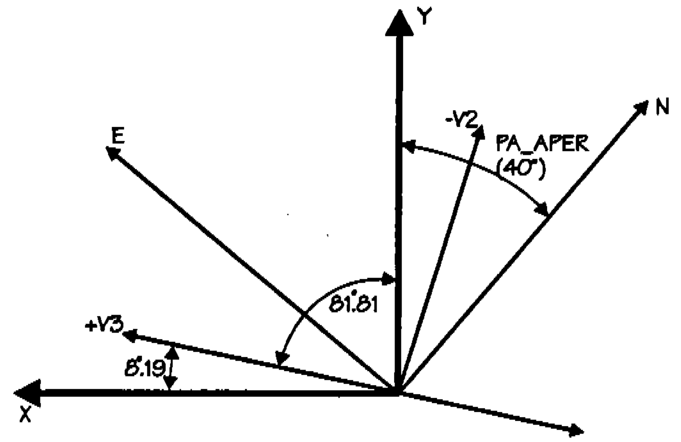


Figure 17.4: Orientation of RED Side, PA_APER=40° in this Example

From the figures above we see that coordinate transformation for the BLUE detector is given by:

$$V2 = X \sin(8.19^\circ) - Y \cos(8.19^\circ)$$
$$V3 = X \cos(8.19^\circ) + Y \sin(8.19^\circ)$$

While the transformation for the RED detector is given by:

$$V2 = X\sin(81.81^\circ) - Y \cos(81.81^\circ)$$
$$V3 = X \cos(81.81^\circ) + Y \sin(81.81^\circ)$$

Aperture Orientation

The position angle of the of the aperture (PA_APER) is the angle in degrees east of North. The header keywords needed to determine the orientation of the aperture on the sky are; PA_APER, RA_APER1 (RA of the aperture center in degrees), and DEC_APER1 (Dec of the aperture center in degrees). See Figures 17.3 and 17.4. Note that PA_APER , RA_APER1, and DEC_APER1 are accurate to about 1". If high precision is required, telemetry data should be used—contact analysis@stsci.edu if this is the case.

Pipeline Calibration of FOS Data

This section describes corrections applied to Faint Object Spectrograph (FOS) data during pipeline processing by the **calfos** task. The first section provides details of how the calibration algorithms are applied, while the second section explains various aspects of the files used in and produced by the calibration process.

Overview of the FOS Pipeline Process

This section describes in detail the pipeline calibration (**calfos**) procedures, as described in detail in "Overview of Pipeline Processing" on page 47. 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 GIMP corrected. ACCUM data are processed up to step 11 (absolute flux calibration) and RAPID, PERIOD, and POLARIMETRY data are processed up to step 12 (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 GIMP correction (OFF_CORR).
6. Do paired-pulse correction (PPC_CORR).
7. Subtract background (BAC_CORR).
8. Do flat field correction (FLT_CORR).
9. Subtract sky (SKY_CORR).
10. Compute wavelengths (WAV_CORR).
11. Perform absolute calibration (FLX_CORR).
12. Do special mode processing (MOD_CORR).

These steps are described in detail in the following sections. A basic flowchart is provided in Figure 5.5 on page 54.

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. Hence, 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.[6] 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 are ignored. At the end of 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. 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

6. Data quality values are described in Table 8.4 on page 86.

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 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.

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 DEFDDTTBL 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 the previous chapter, "FOS Practical Guide," or the *FOS Instrument Handbook* 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.

GIMP Correction (OFF_CORR)

Data obtained prior to April 5, 1993, do not have an onboard geomagnetic-induced image motion problem (GIMP) correction applied, and therefore require a correction for GIMP in the pipeline calibration. It should be noted here that there are some observations obtained after April 5, 1993, that do *not* have onboard GIMP correction, because the application of the onboard GIMP correction depended on when the proposal was completely processed. The GIMP 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. For example, if the amount of the correction for a particular data group is calculated to be +2.38 pixels, data 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 GIMP corrected during the pipeline processing.

The onboard GIMP 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 GIMP 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 GIMP correction is calculated and applied every 30 seconds. The onboard GIMP correction is applied to all observations except the 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 the of these dead time constants in the CCG2 table are; $q_0 = 9.62\text{e-}6$ seconds, $q_1 = 1.826\text{e-}10$ 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, but are not given any data quality value.
- 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 before subtraction. 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.

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

Flat Field Correction (FLT_CORR)

This step removes the diode-to-diode sensitivity variations and fine structure from the object, error, and sky spectra by multiplying each by the inverse flat field response as stored in the FL1HFILE reference file. A second flat field 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 flat fielded 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.

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.

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:

- $l(p)$ – is 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.
- $x0$ – 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.

Absolute Calibration (FLX_CORR)

This step multiplies object (and error) spectra by the appropriate inverse sensitivity vector in order to convert from count rates to absolute flux units (erg s^{-1} cm^{-2} $Å^{-1}$). 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.

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

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 "Data Acquisition Modes" on page 252 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 for each frame is also propagated, in quadrature. 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 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[7]). 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.

7. A complete list of FOS Instrument Science Reports can be found on page 289.

Input, Output, and Reference Files and Tables

In this section, we will describe the various files used by **calfos** during the FOS pipeline calibration process. These files include:

- Input files: these are the observation data files (in GEIS format).
- Reference files (GEIS-format images).
- Reference tables (STSDAS tables).

Input Files

Table 17.7 lists the science files required as input to **calfos**. These files are described briefly below. See also "Understanding Your Data" on page 15.

Table 17.7: Observation Input Files Required by 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 for 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 done 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.
- *Data dropouts* and *filled 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. A complete listing of data quality flag values is provided in "Using Data Quality Files" on page 85.

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 files are of the form .cy*n*, .r*n*h and .r*n*d where *n* represents a value from 0 to 8 (see Table 17.8). These files are maintained in the CDBS by STScI. STEIS maintains an updated catalog of these tables and files.

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.

Table 17.8: 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	GIMP correction scale factors
CCS8	cyccs8r	.cy8	Predicted background (count rate)
CCG2	coccg2r	.cmg	Paired-pulse coefficients
BACHFILE	cybacr	.r0h & .r0d	Default background file (count rate)
FL*n*HFILE	cyfltr	.r1h & .r1d	Flat field file
IV*n*HFILE	cyivsr	.r2h & .r2d	Inverse sensitivity file (ergs cm^{-2} $Å^{-1}$)
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

Reference Tables

The CDBS relations for the FOS reference files and reference tables are described below.

- **cyccs0r:** This table is used to determine the aperture area for paired apertures.
- **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.
- **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 wave plate 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 used to generate wavelength scales. There is one entry for each detector, disperser, aperture, and polarizer combination.
- **cyccs7r:** GIMP 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.
- **coccg2r:** Paired pulse correction table used to correct for non-linear response of each diode. 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 flat field 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 473) or by checking the information on inverse sensitivity files on STEIS which are updated with each delivery of new files. Figures 17.5 and 17.6 show the inverse sensitivity for the most commonly-used gratings for both detectors.

Figure 17.5: Inverse Sensitivity Reference Files for Blue High Dispersion Gratings

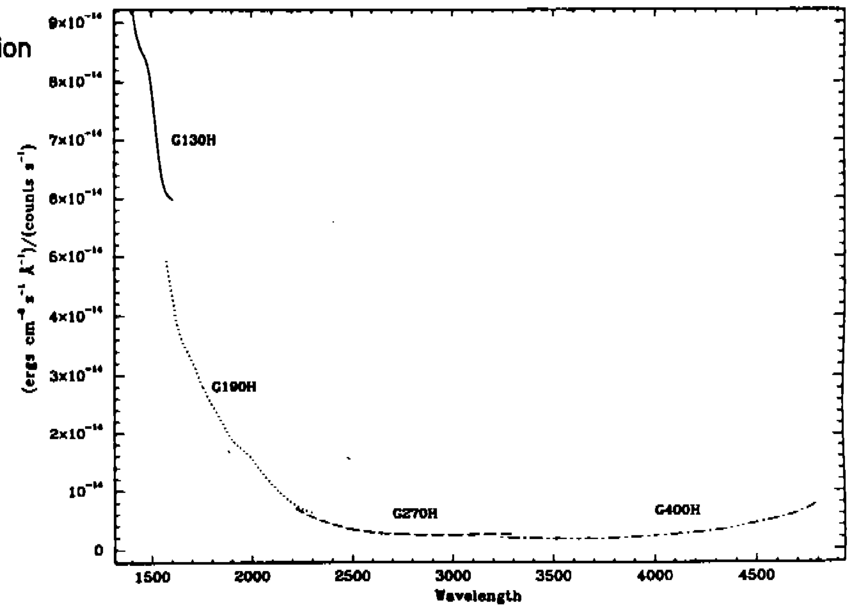
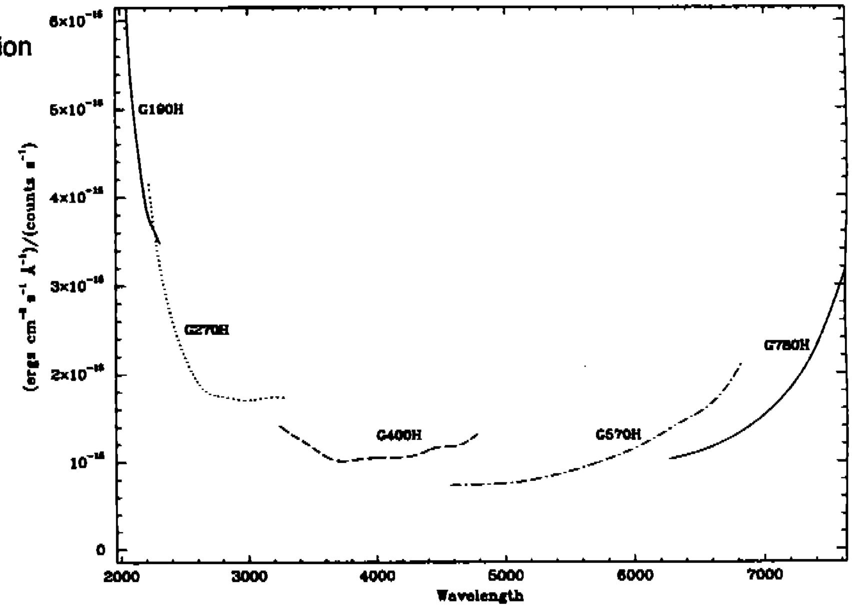
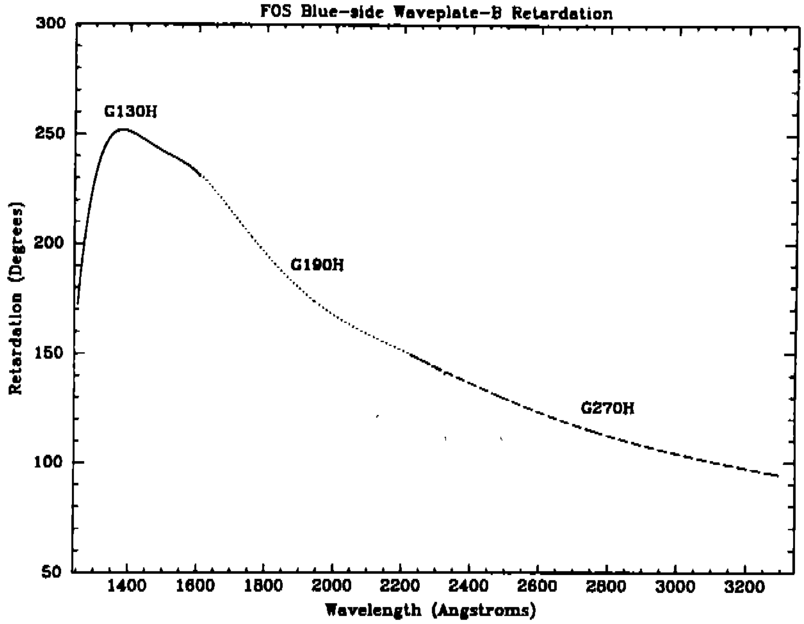


Figure 17.6: Inverse Sensitivity Reference Files for Red High Dispersion Gratings



- **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 17.7 with the appropriate grating shown.

Figure 17.7: Retardation Reference File



- **cyddtr:** This is the relation is 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 .u1h file. The disabled diode table is updated and information on this is found on STEIS. The total number of disabled blue diodes is 25 and disabled red diodes is 15, as of December 1993. Note that the diodes in the Tables 17.9 and 17.10 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.

Table 17.9: Blue Detector Disabled Diodes as of December 1993

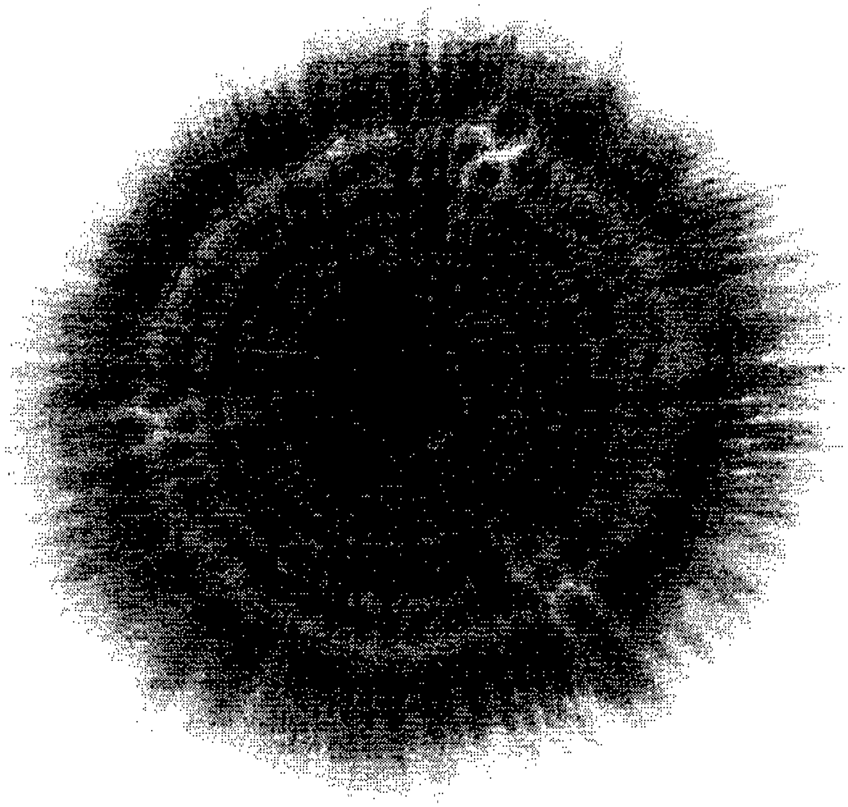
DISABLED Dead Channels	DISABLED Noisy Channels	DISABLED Cross-Wired Channels	ENABLED But Possibly Noisy
49	31	47	8
101	73	55	138
223	144		139
284	201		209/210
292	218		421
409	225		426
441	235		
471	241		
	268		
	398		
	415		
	427		
	451		
	465		
	472		
	497		
8	16	2	6

Table 17.10: Red Detector Disabled Diodes as of December 1993

DISABLED Dead Channels	DISABLED Noisy Channels	ENABLED But Possibly Noisy
2	110	153
6	189	142
29	285	174
197	380	258/259
212	381	261
308	405	410
486	409	
	412	
7	8	6

- **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 17.8, a sample blue side FOS PSF at 1400 Å is shown.[8]

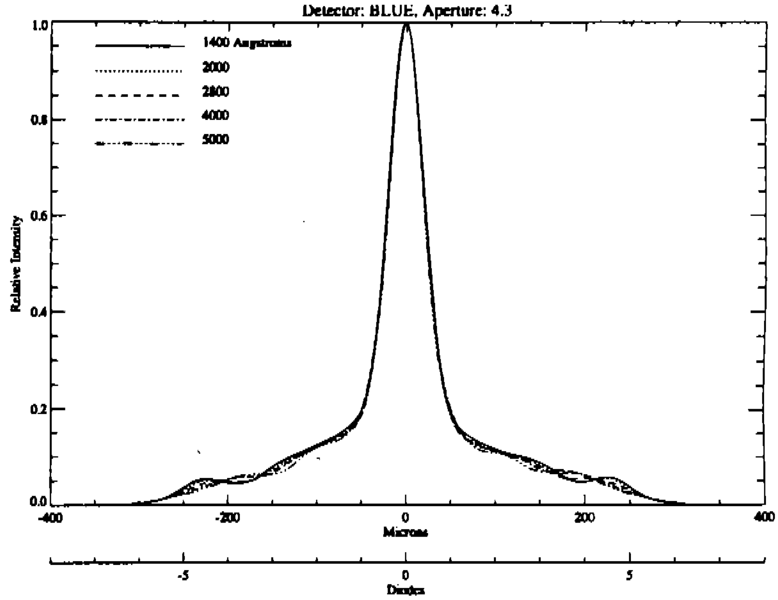
Figure 17.8: Example of a Pre-COSTAR Point Spread Function for the FOS



- **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 17.9 shows a sample monochromatic FOS LSF for the blue side 4.3" aperture. LSFs are available at each PSF wavelength.[5]

8. *FOS Instrument Science Report* 104.

Figure 17.9: 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.*

Post-Calibration Output Files

Several types of calibrated output files are produced by **calfos**. These are listed in Table 17.11. More extensive descriptions of each type of file are provided below.

Table 17.11: 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	Flat fielded object count rate spectrum
.c6h and .c6d	Flat fielded sky count rate spectrum
.c7h and .c7d	Background count rate spectrum
.c8h and .c8d	Flat fielded and sky subtracted object count rate spectrum

The calibrated output files listed in Table 17.11 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 also 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 8.4 on page 86. The data quality files are identified by extensions `.cqh` and `.cqd`.
- **Calibrated statistical error files:** These files have 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 are not calculated and updated.* The errors files are identified by extensions `.c2h` and `.c2d`.
- **Special mode data files:** Data acquired in the rapid-readout, time-resolved, or spectropolarimetry modes resulting from this additional processing are stored in these 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 polarizations, 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. The special mode data files are identified by the extensions `.c3h` and `.c3d`.
- **Intermediate calibrated output files:** At most, five sets of intermediate calibrated output files are produced depending on the observation strategy. 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 flat fielded object spectrum files are identified by the extensions

.c5h and .c5d. The flat fielded 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.

Acknowledgement

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18 Other Sources of FOS Information

In This Chapter...

This chapter is simply a listing of other documents provided by the STScI that deal with various aspects of the Faint Object Spectrograph. These documents can be requested through the User Support Branch via e-mail to: usb@stsci.edu.. This listing is current as of January 1994, however, new documents are frequently added so the listing on STEIS will always be more current.

Instrument Science Reports

- 001 – *Lab. Calibration of the FOS: Absolute Sensitivity (First Results for the Blue Side)*, J. Koornneef, R. Bohlin and R. Harms, August 1983.
- 002 – *FOS Entrance Aperture Sizes*, J. Wheatley, R.C. Bohlin, and H. Ford, October 1983.
- 003 – *Recent FOS Calibration at GSFC*, J. Wheatley and R. Bohlin, November 1983.
- 004 – *FOS Wavelength Calibration*, J. Wheatley and R. Bohlin, December 1983.
- 005 – *FOS-Scattered Red Light (Red Tube)*, J. Koornneef, January 1984.
- 006 – *FOS Flat Field Calibration (FOS Calibration #15)*, D. Lindler and R. Bohlin, March 1984.

- 007 – *FOS Scattered Light Measurements (Cal. Plan #128)*, J. Wheatley and R Bohlin, March 1984.
- 008 – *FOS Aperture Repeatability & Filter–Grating Wheel Repeatability (Calibration Plan 10C & 10D)*, J. Wheatley, H. Ford, and R. Bohlin, March 1984.
- 009 – *FOS Firmware Target Acquisition*, H. Ford, June 1984.
- 010 – *High Voltage Settle (FOS Calibration #08)*, D. Lindler and R. Bohlin, December 1984.
- 011 – *Scattered Light Background Perpendicular to the Dispersion—Preliminary Version (Calibration #19)*, D. Lindler and R. Bohlin, January 1985.
- 012 – *FOS Filter Grating Wheel Repeatability (Calibration Plan 10D)*, G. Hartig, R. Bohlin, H. Ford, and R. Harms, December 1984.
- 013 – *Scattered Red Light—Preliminary Version (Calibration Plan 12A)*, M. Sirk and R. Bohlin, January 1985.
- 014 – *Internal FOS PT-CR-Ne Calibration Lamps—Performance in the Far UV,* M. Sirk and R. Bohlin, March 1985.
- 015 – *Scattered Light from Bright Emission Lines Preliminary Version (Calibration Plan 12B)*, M. Sirk and R. Bohlin, March 1985.
- 016 – *Absolute Photometric Calibration of the FOS*, G. Hartig, June 1985.
- 017 – *Improvements in Filter/Grating Wheel Repeatability*, G. Hartig, May 1985.
- 018 – *FOS Line Widths (FWHM) as a Function of Aperture Size*, A. Kinney and H. Ford, May 1985.
- 019 – *FOS Entrance Aperture Sizes (Calibration Plan 10B)*, D. Lindler and R. Bohlin, July 1985.
- 020 – *Scattered Light from Bright Emission Lines (Calibration Plan 12B)*, M. Sirk and R. Bohlin, September 1985.
- 021 – *LMSC NSSC-1 Target Acquisition Tests of Feb. 1985*, D. Lindler, A. Kinney, and H. Ford, September 1985.
- 022 – *Locating Spectra on the FOS Digicons & The Photometric Consequences of Errors in Position, Oct. 1985*, J. Wheatley and R. Bohlin, October 1985 (never completed).
- 023 – *Mode 2 Target Acquisition: Binary Search Parameters, Oct. 1985*, A. Kinney and H. Ford, October 1985.
- 024 – *Results of Binary Search Target Acquisition Tests of August, 1985*, A. Kinney and H. Ford, November 1985.

- 025 – *FOS Linearity Corrections - Jan. 1986*, D. Lindler and R. Bohlin, January 1986.
- 026 – *FOS Wavelength Calibration - Jan 1986 (Laboratory Calibration Plan 13b)*, M. Sirk and R. Bohlin, January 1986.
- 027 – *Firmware Target Acquisition*, A. Kinney, R.G. Hier, and H. Ford, June 1986.
- 028 – *Exposure Times for FOS Wavelength Calibration—Apr. 1986*, M. Sirk and R. Bohlin, April 1986.
- 029 – *FOS Entrance Aperture Offsets (Calibration Plan 136)*, M. Sirk and R. Bohlin, May 1986.
- 030 – *Limiting Magnitudes for FOS Target Acquisition*, A. Kinney, April 1986.
- 031 – *Commanding FOS Target Acquisition*, T.M. Gasaway and A. Kinney, June 1986.
- 032 – *An Automated Method for Computing Absolute Instrumental Sensitivity Curves for FOS: Results of Testing on IUE*, D. Lindler and R. Bohlin, August 1986.
- 033 – *Thermal Vac Measurements of the FOS Filter Grating Wheel Repeatability*, G. Hartig, August 1986.
- 034 – *FOS Throughput Optical Test Results*, G. Hartig, August 1986 (never completed).
- 035 – *Results of TA Tests at LMSC: Feb. 1986*, A. Kinney, August 1986.
- 036 – *TV Monitoring of the F8 Detector Red Sensitivity (Test Segment MONTHLY)*, G. Hartig, August 1986.
- 037 – *Ambient QE Measurements of the FOS Red Side*, G. Hartig, October 1986.
- 038 – *FOS Wavelength Scale Below the Calibration Lamp Cutoff at 1239A (Lab. Calibration Plan 13B)*, M. Sirk and R. Bohlin, October 1986.
- 039 – *FOS Entrance Aperture Transmittance for Point Sources*, G. Hartig, November 1986.
- 040 – *Results of Target Acquisition Tests: Feb. 1987*, A. Kinney, March 1987.
- 041 – *Wavelength Offsets Among Internal Lamps and External Sources*, M. Sirk and R. Bohlin, April 1987.
- 042 – *FOS Target Acquisition for Moving Targets*, A. Kinney, June 1987 (never completed).
- 043 – *FOS Target Acquisition Cook Book*, A. Kinney and R. Antonucci, May 1988.

- 044 – *Limiting Accuracy of FOS Wavelengths Calibration*, R. Bohlin, M. Sirk, and G. Hartig, October 1987.
- 045 – *FOS Linearity Corrections (Revisited)*, D. Lindler and R. Bohlin, August 1988.
- 046 – *FOS Aperture Wheel Repeatability*, R. Harms and R. Downes, October 1988.
- 047 – *FOS Exposure Limits*, G. Hartig, October 1988.
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- 050 – *FOS Discriminator Settings*, R. Cohen, E. Beaver, and D. Tudhope, May 1990.
- 051 – *Dead and Noisy Diode Summary*, R. Cohen, April 1989.
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- 053 – *Laboratory Calibration of FOS Throughput*, G. Hartig, January 1989.
- 054 – *Revised FOS Wavelength Calibration*, G.A. Kriss, W.P. Blair, and A.F. Davidsen, November 1988.
- 055 – *FOS Polarimetry*, R.G. Allen and P.S. Smith, November 1988 (never completed).
- 056 – *FOS Internal/External Wavelength Offsets*, W.P. Blair, G. A. Kriss, and A.F. Davidsen, December 1988.
- 057 – *Image Drift After HV Turn-on*, W. Baity and E. Beaver, February 1989.
- 058 – *Scattered Red Light in the FOS*, W. P. Blair, A.F. Davidsen, and A. Uomoto, March 1989 (never completed).
- 059 – *Scattered Light Perpendicular to the Dispersion in the FOS*, A. Uomoto, W.P. Blair and A.F. Davidsen, March 1989.
- 060 – *FOS Filter-Grating Wheel Repeatability: Dependence on Motor Selection*, G. Hartig, May 1989.
- 061 – *FOS Optical Focus and Resolution*, T. Ed Smith and G. Hartig, October 1989.
- 062 – *Long Term FOS Calibration Plan*, A.L. Kinney and G.F. Hartig, August 1989.

- 063 – *FOS Project Data Base Aperture Files*, A.L. Kinney and C. Cox, October 1989.
- 064 – *FOS Dead and Noisy Channel Update*, R. Cohen and E. Beaver, October 1989.
- 065 – *The Rotation Matrix for Calculating V2, V3 Offsets in Mode 2 FOS TA*, A.L. Kinney and G. Hartig, March 1990.
- 066 – *Geomagnetic Image Deflection Problem in the Faint Object Spectrograph*, V.T. Junkkarinen, E.A. Beaver, R.D. Cohen, R. Hier, R. Lyons, and E. Rosenblatt, April 1992.
- 067 – *In-Flight FOS Wavelength Calibration–Template Spectra*, G.A. Kriss, W.P. Blair, and A.F. Davidsen, February 1991.
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- 070 – *Internal/External Offsets in the FOS Wavelength Calibration*, G.A. Kriss, W.P. Blair, and A.F. Davidsen, February 1992.
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- 077 – *Photometric Calibration of the FOS*, J. D. Neill, R. C. Bohlin, and G. Hartig, June 1992.
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- 085 – *FOS Aperture Throughput Variations with OTA Focus*, D. Lindler and R. Bohlin, August 1992.
- 086 – *Analysis of Photometric Standards following July 1992 FOS Over-light Safing Event*, C. J. Taylor and C.D. Keyes, December 1992.
- 087 – *FOS Blue Detector Plate Scale and Orientation*, A. Koratkar, May 1993.
- 088 – *FOS Flats From Super Spectra*, D. Lindler, R. Bohlin, G. Hartig, and C. Keyes, March 1993.
- 089 – Primary author: T. Keyes
- 090 – *FOS Flat Field Reference Files: A Quick Reference Guide to the Appropriate File for a Particular Date and Instrumental Configuration*, C. Keyes and C. Taylor.
- 091 – *A Rough Photometric Calibration for FOS, BLUE, G160L, ORDER0*, K. Horne and M. Eracleous, August 1993.
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- 093 – *FOS Inverse Sensitivity Reference Files: A Quick Reference Guide to the Appropriate File for a Particular Date and Instrumental Configuration*, C.J. Taylor and C.D. (Tony) Keyes, June 1993.
- 094 – *FOS Calibration Plan for Cycle 3*, C. D. (Tony) Keyes and A. Koratkar, June 1993.
- 095 – *Location of FOS Polarimetry*, Anuradha Koratkar and C.J. Taylor, June 1993.
- 096 – *Location of FOS Spectra: Cycle 1 and Cycle 2 Results*, A. Koratkar and C. J. Taylor, August 1993.
- 097 – *Light Loss in FOS as a Function of Pointing Error*, R.C. Bohlin, August 1993.

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- 100 – *Cycle1/Cycle2 Discriminator Settings,* C.J. Taylor and A.L. Kinney, February 1994.
- 101 – Authors: R. Gilmozzi and E. Kinney
- 102 – *FOS Aperture Throughput Variations Due to Focus Changes,* D.L. Lindler and R.C. Bohlin, August 1993.
- 103 – *Background Due to Scattered Light,* A.L. Kinney and R.C. Bohlin, September 1993.
- 104 – *Pre-COSTAR FOS Point Spread Functions and Line Spread Functions from Models,* I.N. Evans, September 1993.
- 105 – *Pre-COSTAR FOS Aperture Throughputs from Models,* I.N. Evans, September 1993.
- 106 – *Pre-COSTAR FOS Aperture Transmissions for Point Sources and Surface Brightness of Diffuse Sources,* R.C. Bohlin, October 1993.
- 107 – *Pre-COSTAR FOS Aperture Throughputs for Mis-centered Targets Derived from PSF Models,* I.N. Evans, November 1993.
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- 119 – *The Faint Object Spectrograph Binary Search Target Acquisition Simulator BS4,* I Evans, February 1994.

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