

The Closeout State of the Faint Object Spectrograph

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Abstract. The Faint Object Spectrograph (FOS) was one of the original HST instruments and was removed from the spacecraft in February, 1997. We present a summary of the state of FOS calibration accuracies as of fall 1997. Modest background information about each of the various calibrations and instrumental operating conditions that limit calibration accuracy is also provided. We also reference other useful documentation for more in-depth discussion of these topics.

1. Introduction

This presentation will focus on a summary of the calibration status of the FOS as of fall, 1997. Much of what is presented here is based directly upon the results of the FOS Closeout Calibration re-analysis of on-orbit data performed since the de-commissioning of the instrument in February, 1997.

The primary recommendation of this presentation is that *all FOS data, no matter when or how they were obtained, should be re-calibrated* with the closeout reference files and current `calfos` algorithms in order to achieve the highest degree of calibration accuracy and data quality. Secondly, you should refer to the FOS WWW page (under the STScI page at <http://www.stsci.edu>) for the latest calibration information.

For a thorough technical-level description of the FOS instrument please refer to the FOS Instrument Handbook version 1.1. For descriptions of typical on-orbit usage and operating concerns see FOS Instrument Handbook version 6. Volume II of the forthcoming *HST Data Handbook* (DH) version 3, to be issued in January, presents much of the following material with greater elaboration. The new DH is the primary reference for all questions pertaining to FOS calibration and analysis.

The Faint Object Spectrograph (FOS) was one of the five original instruments on HST. The FOS was a single-pass spectrometer with six high-dispersion ($R = 1300$) and two low-dispersion ($R = 250$) blazed, ruled gratings and one sapphire prism. Two separate Digicon detectors were available to provide coverage of the entire wavelength range from 1150 to 8400 Å with redundancy between the detectors in the range 1650-5400 Å. The FOS/BL detector was sensitive between 1150 and 5400 Å and the FOS/RD between 1650-8400 Å. FOS/RD was more sensitive at all wavelengths longward of 1700 Å, but also had a higher detector background, more substantial photocathode changes, and less effective magnetic shielding. The spectra were recorded by 512 diodes each of which were 0.35 arcsec wide (x-coordinate parallel to dispersion) and 1.43 arcsec in height in the pre-COSTAR setup. Post-COSTAR dimensions were 0.31 arcsec wide by 1.29 arcsec in height.

Not all FOS data, particularly those from the pre-COSTAR era, were acquired with optimal target acquisition procedures or with optimal instrumental settings. Although the effort is not as intrinsically interesting as interpretation of the science data, we strongly urge you to analyze the quality of the target acquisition for your data and, based upon the following information and that in the DH, understand its impact on your science exposures.

As we shall see, the quality of all FOS data is governed by the location of the target in the aperture (determined by the target acquisition employed), the location of the target

image on the photocathode (most strongly affected by filter-grating wheel positioning), and the location of the photocathode image on the diode array (controlled by the Y-base). Therefore, you should assess the limitations that each may place on your observational material.

Target acquisition centering affected

- the amount of light transmitted by the aperture, hence the photometric accuracy of the observations,
- the degree to which calibrated photocathode granularity was sampled, hence the limiting S/N after flatfield correction,
- the centering of the beam on the grating parallel to dispersion, hence the wavelength accuracy, and
- for larger apertures the positioning of the image on the photocathode with respect to those portions of the photocathode that were sampled by the diode array.

The position of the target on the photocathode affected

- wavelength calibration and
- the correct sampling of photocathode granularity.

Incorrect sampling of the output photocathode image for larger apertures affected both

- the absolute photometric accuracy of the observations and, especially
- the shape of the spectrum.

In the following we will assess the ranges of variation associated with the instrumental effects that limit FOS calibration accuracies and will then discuss the various calibration accuracies themselves.

2. Instrumental and Operational Limitations

2.1. Y-bases

The FOS Y-base is the amount of magnetic deflection required to ensure that the photocathode output image is directed onto the diode array. Depending upon the changing magnetic environment of the detector, differing amounts of deflection may have been required at different times to direct phototelectrons from a particular place on the photocathode to a particular place on the Digicon detector. The Y-base was measured in ybase units of which 256 were always defined to equal the diode height (1.29 arcsec post-COSTAR and 1.43 arcsec pre-COSTAR).

Repeated independent observations of the same Y-base yield an external ± 25 ybase scatter (0.14 arcsec pre-COSTAR; 0.12 arcsec post-COSTAR) which is attributable to residual geomagnetic image motion (GIM) and filter-grating wheel position non-repeatabilities. The internal measurement error associated with any Y-base measurement is ± 5 ybases.

The images of FOS spectra were curved on the photocathode. These so-called *s-curves* typically ranged ± 20 ybases about a midrange value. The nature of the FOS design required that an average Y-base be used for the entire spectrum. If curvature were substantial, and the target were displaced toward the edge of an aperture, the diode array might not sample all of the dispersed image.

Clear temporal trending existed for the nominal position of FOS/BL Y-bases, while the trending was less clear for FOS/RD. Y-bases were updated approximately every six months so that installed values were usually within 10 ybases of the nominal trend line. In certain cases, notably FOS/BL G130H between February and November, 1994, considerably larger deviations existed which had noticeable color-dependent photometric effects.

The photometric impact of an erroneous Y-base depended upon the size of the error, the aperture involved, and the detector-disperser combination employed. On the average, for post-COSTAR point sources observed with the 1.0 and larger apertures, an error of 20 ybases could produce a 3-5% general light loss and up to 10% at certain wavelengths where the s-curvature was substantial - typically near the edges of the spectral regions. The light loss was larger, but harder to simply quantify, for pre-COSTAR point sources and all observations of extended sources.

Y-base uncertainties have essentially no photometric impact for observations with apertures smaller than 1 arcsec in size as the displacements required to place these aperture images off the diode array are simply much larger than the observed uncertainties.

Summary: For large aperture (1 arcsec and larger) observations, Y-base uncertainty is a prime contributor to photometric, especially spectral shape, uncertainties in FOS data. There is little or no photometric effect for apertures smaller than 1 arcsec.

2.2. Mechanism Stability and Image Motion

The positions of the FOS filter-grating wheel (FGW) were stabilized by notches or detents. There was some mechanical non-repeatability of the wheel position on separate visits to the same notch. The x-component of any FGW positioning uncertainty caused an offset in the observed wavelengths from the calibrated dispersion relation. An offset in either x or y added a small uncertainty to the flat field calibration.

The FOS aperture wheels could also suffer some non-repeatability of their positional alignments, but the sizes of aperture wheel non-repeatability were an order of magnitude smaller than FGW non-repeatability. As such, aperture wheel non-repeatability had no significant impact on any FOS calibration uncertainty.

FOS image motion could be produced by the combined effects of GIM motions and guiding errors. In the pre-COSTAR period before routine onboard GIM motion correction was implemented (5 April 1993), typical image motion was of the order of 0.15 arcsec. A post-observation correction for the x-component of this motion was made in standard pipeline calibration, which was accurate to the nearest pixel (0.044 arcsec or, at high dispersion, 30 km/sec). No post-observation correction was possible for the y-component of this motion, which could be up to 25 ybases in size.

Following the implementation of an onboard correction, residual peak image motions were reduced to approximately 0.02 arcsec. The one sigma uncertainty in x was 0.06 diodes (0.25 pixel or about 15 km/sec at high dispersion). The one sigma residual in y was about 5 ybases.

2.3. Target Acquisition

Pre-COSTAR FOS ACQ/BINARY target acquisition accuracies were typically 0.12 arcsec (one sigma) in addition to 0.15 arcsec due to GIM (prior to 5 April 1993). Post-COSTAR ACQ/BINARY one sigma accuracies were 0.08 arcsec for FOS/BL and 0.12 arcsec for FOS/RD. ACQ/PEAK accuracies were always determined by the photon statistics and the step-size of the last pattern employed in the acquisition sequence. The worst-case pointing accuracy of the finest pattern used in FOS acquisitions was 0.025 arcsec in each coordinate.

3. FOS Calibration Results

3.1. Flux Calibration Accuracy

The overall limiting FOS photometric calibration accuracy is approximately 3% (one sigma). This overall accuracy is composed of the following components:

- 2% or smaller systematic residuals for comparison of FOS fluxes with the white dwarf pure hydrogen model atmospheres that define the HST flux system.
- <1% (one sigma) residuals in Landolt visible photometry used to normalize the flux system.
- 1% (one sigma) internal FOS repeatability, which is the ultimate limiting accuracy of the determination of spectral shape.

Additional factors may limit the accuracy of individual FOS observations, in particular:

- Absolute and relative accuracies are limited by Y-base uncertainties for apertures 1 arcsec and larger. These effects depend upon aperture, grating, and target acquisition.
- Precision absolute spectrophotometry required precise pointing (<0.06 arcsec or better).
- Precision relative spectrophotometry required precise pointing (<0.06 arcsec or better) for apertures larger than 0.5 arcsec.
- FOS/RD G780H accuracy is somewhat worse (about 4% one sigma) due to lower S/N in the fewer observations of standard stars and more uncertainty in flatfields.
- Small aperture throughput could be affected by breathing. Documented smooth trends of as much as 3-4% have been seen for well-centered targets in the post-COSTAR small apertures. Pre-COSTAR small aperture photometry was affected to a greater degree (perhaps as much as 7%) and was further compromised by the effects of jitter and guiding.

Many early pre-COSTAR programs did not utilize precise acquisitions. As a result, the photometric quality of these observations is diminished (see Koratkar and Evans, this volume). It is essential that the impact of the target acquisition on any FOS observation be assessed, and especially for pre-COSTAR data,

The influence of Y-base errors on FOS photometry is not fully characterized at this writing. FOS calibration program 6916 contains two visits of data obtained in December 1996 and January 1997 that may be helpful to GOs who wish to assess the impact of Y-base uncertainty on their data. These observations consist of RAPID mode readouts of FOS standard star BD+28D4211 as it was drifted perpendicular to dispersion across the 1.0 and 4.3 apertures at pre-determined rates.

3.2. Flatfield Calibration

FOS flatfields are designed to remove photocathode irregularities with typical dimensions of 10 pixels or less. Our cumulative experience with the FOS detectors has shown that the amount of photocathode structure or granularity varies as a function of time, spectral element, and photocathode location. As a result it is important to use flatfields taken as nearly contemporaneously as possible with the exposure to be calibrated. The FOS calibration observations from which flatfields are produced always used the highest precision acquisition available, namely 0.025 arcsec or better accuracy in each coordinate. In order

to achieve optimum flatfield correction it was necessary to sample the same portion of the photocathode as was used for the flatfield calibrating exposures, hence the same high degree of pointing accuracy was required.

Two different techniques have been used to produce FOS flatfields: the superflat method and the continuum-fit method. Please refer to the *HST Data Handbook* and FOS ISRs 088 and 134 for details on the methods, but we note that superflats are much more objective and are the superior product.

FOS flat field status: Post-COSTAR aperture-dependent flatfields have been prepared for all standard star observations of standards G191B2B and BD+28D4211. All post-COSTAR FOS flatfields are based on or derived from superflat observations. The apertures include 4.3, 1.0, 0.3, 1.0-PAIR, and 0.25-PAIR. Pre-COSTAR flatfields for the 4.3 aperture are available for 1992-93, but flats for earlier periods are not based on superflats. In the pre-COSTAR epoch few flats for apertures other than 4.3 are available, but given the larger PSF, this is not a serious problem for the single apertures. The relative lack of paired aperture pre-COSTAR flatfields is a limiting factor, however, as photocathode granularity can be quite different at the paired aperture locations.

New flatfields delivered as part of the FOS closeout calibration increase the accuracy of correction for temporally variable features, particularly in the FOS/RD G190H 1950 and 2150 Å, FOS/RD G400H 4475 Å, and FOS/BL G160L 1550 Å regions.

High S/N observations ($S/N > 30$) always required pointing accuracy of 0.06 arcsec or better.

Some x-shifting of the granularity (typically +/- 1 pixel) relative to the standard star epoch did occur with the FOS due to residual GIM and other magnetic effects. If a persistent feature is not adequately removed by flatfielding with the closeout flats, we recommend shifting the spectrum by +/- 1 or 2 pixels and re-flatfielding. This procedure typically shows little improvement for $S/N < 30$, but can be of use in higher S/N situations. As a related item, we note that arbitrary shifting of highly accurate standard star observations by only 1 pixel prior to flatfielding introduces obvious pattern noise at the 1-2% level. Fractional pixel shifts, caused by residual image motion effects will likewise introduce similar noise in nearly any FOS exposure.

FOS flatfielding accuracies:

- 1% limiting RMS can be achieved with post-COSTAR superflat-based flats, high photon statistical S/N, precise aperture centering, and excellent x-coordinate alignment with the flatfield. Accuracies of 2-3% are more typical for precisely centered observations. .
- input calibration data typically had counting statistics S/N of 40:1 to 200:1
- substantial improvement (5-25%) is achieved relative to the original pipeline flats in certain wavelength regions for tracking of flatfield features (e.g., at 1950, 2150, 4475, and 1550 Å),
- Time-sampling frequency is variable. Some trends (e.g., 5% changes at FOS/RD G400H 4475 Å between June 1995 and April 1996 are not sampled well).

Flatfield suggestions: Remember that FOS flatfields are not interpolated between standard star epochs and USEAFTER dates are chosen to represent midranges of time periods. As we have recommended in previous workshops and in the *HST Data Handbook*, detailed comparison of your data with the nearby (before and after) standard star observations and their attendant flatfields can be very helpful in determining the veracity of any particular feature.

3.3. Wavelengths

FOS pipeline wavelengths should be considered only an approximation to the actual wavelength scale appropriate to any exposure due to the influence of a variety of instrumental and observing effects. Some of these sources of error can be removed if a contemporaneous WAVECAL was taken immediately before or after the science exposure *without* any motion of the FOS filter-grating wheel between the exposures.

Since the FOS pipeline wavelength solution is based upon a single set of dispersion fits made at one epoch of observation, a potentially large systematic wavelength offset may be present in the calibrated wavelengths for any observation that does not have a contemporaneous WAVECAL. A recent re-examination of the pipeline fits has indicated that the filter-grating wheel position for several of the defining WAVECAL observations may have been near an extremum of its range (one sigma filter-grating wheel uncertainty is of the order of 0.12 diodes).

The net effect is that a systematic offset of up to 1 diode width (250 km/sec at high dispersion) may be present in many calibrated wavelength sets. This offset can be removed by forming a mean set of wavelength coefficients that are more representative of the actual range of filter-grating wheel motion for each disperser. This update is currently in progress and will be reported on the FOS WWW page when available.

In the meantime, for those observations with a contemporaneous WAVECAL, FOS wavelength accuracies are affected by the following contributions to the error budget:

- target centering: (worst-case for best acquisition scenario is 0.025 arcsec or 0.08 diode). All observers must assess for their particular case.
- residual image motion (GIM or other): 0.06 diode (one sigma)
- line-measurement: 0.02 diode (typical one sigma).
- dispersion fit rms: typically 0.04 diode
- spacecraft orbital motion: 0.034 diode (upper limit)

Remember that no correction is made in the pipeline for any motion of the spacecraft, so that heliocentric motion may also be important.

3.4. Polarimetry

The pre-COSTAR polarimetry calibration stands as provided by the 1994 reference files. The post-COSTAR calibration is being re-worked at this writing to include a special correction for the influence of COSTAR-induced instrumental polarization. This new correction will be included in the next release of `calfos`.

All FOS polarimetry fluxes are on the white dwarf reference system. At this writing, all polarimetry data in the HST Archive must be re-calibrated.

Polarimetry accuracies: Pre-COSTAR polarization accuracies were limited by the effects of residual GIM motion, filter-grating wheel positioning, and jitter on the fraction of the large PSF s-curve that was actually recorded by the diode array. Variations in these quantities produced scatter in total polarization of the order of 0.5% and occasionally somewhat worse. The uncertainty in the retardation calibration also contributed a systematic instrumental polarization equal to 2% of the linear polarization. Actual observing limits were often imposed by the photon statistics of the data.

Post-COSTAR total polarization residuals of approximately 0.1% may be achieved after correction for instrumental polarization throughout most of the 1600-3300 Å region. In the 1800-2100 Å region the limit is approximately 0.2%. Again the uncertainty in the retardation calibration contributes an additional systematic uncertainty of 2% of the linear

polarization. Although all FOS polarimetry calibrations were taken with 16 polarizer rotation steps and a minimum of 8 steps was recommended, some polarimetry observations used only 4 rotation positions. These cases contain an additional 0.4% uncertainty in total polarization. Again, photon statistics are nearly always the limiting factor in individual polarimetry measurements.

3.5. Aperture Locations and Plate Scale

No precise measurement of the pre-COSTAR FOS aperture locations was attempted. The absolute location of the 4.3 aperture was determined with approximately 1 arcsec accuracy. Each single aperture was assumed to be concentric with the 4.3; an assumption not borne out by post-COSTAR measurement.

Post-COSTAR aperture locations were more precise. The absolute location of the 1.0 aperture was determined with 1 sigma accuracies of 0.24 arcsec and 0.30 arcsec for FOS/BL and FOS/RD, respectively. All relative aperture locations, except for that of the 4.3, were determined with 0.02 arcsec (1 sigma) accuracy. The accuracy of the relative position of the 4.3 was approximately 0.1 arcsec. All single apertures but the 4.3 were concentric as were all paired apertures except the 1.0-PAIR. Details may be found in FOS ISRs 137 and 139.

Pre-COSTAR plate scale was 0.0896 arcsec per pixel in each coordinate. Post-COSTAR plate scale (arcsec per pixel) values were $x=.0774$, $y=.0786$ (FOS/BL) and $x=.0752$, $y=.0812$ (FOS/RD). All post-COSTAR one sigma uncertainties were $\pm .001$ arcsec per pixel.

3.6. Background

FOS detector background was produced by high-energy particle events within the detector. Cerenkov radiation produced light as particles hit the faceplate and occasionally the particles themselves hit the detector and produced spurious counts. Variations in mean rates of up to a factor of 1.5 were correlated with geomagnetic latitude, but no longitude, solar position angle, or solar cycle effects were seen. The pipeline model background deviates from fits to the dark observations by up to 20% at high latitudes.

Mean detector background:

- FOS/BL = 0.007 counts/sec/diode;
- FOS/RD = 0.01 counts/sec/diode

Mean particle-induced background levels were scaled by the ambient geomagnetic field to produce the pipeline background correction. Since the dark contribution in short exposures was dominated by individual events that usually affected individual diodes, many FOS exposures - and all readouts - were not lengthy enough to allow a uniform dark distribution to build up at sufficiently high S/N for the pipeline mean correction to have high accuracy. Random excursions of at least a factor of two about the mean level were often seen. Examination of the paper products is useful in assessing the quality of background correction. For more details please refer to the *HST Data Handbook*.

3.7. Dead and Noisy Diodes

Over the lifetime of the FOS diodes occasionally began to perform spuriously and, in some cases, to quit working altogether. The FOS team followed the general rule of disabling any diode that exhibited three separate dead or noisy occurrences. Upon the disabling of the diode, a new dead diode reference file was produced that contained an effective date of the *first* reported occurrence of anomalous activity by the diode.

As part of the closeout, the dead diode files are now complete. Naturally, any unreported earlier occurrences of a disabled diode will not be corrected by the final reference

files. As well, several diodes had fewer than three anomalous events over the lifetime of the FOS. Such events are also not tagged by the closeout dead diode reference files.

3.8. LSF/PSF

A detailed series of pre-COSTAR computed PSFs and LSFs is available from CDBS (see FOS ISRs 104 and 105 for details of these models). No post-COSTAR theoretical LSFs or PSFs are available, but observational dispersed light LSFs were examined from comparison arc lines and in spectra with nominally unresolved emission lines.

These post-COSTAR LSFs display typical Voigt profiles. For $S/N < 10$ only a Gaussian core is evident, but at higher S/N with the 4.3 and 1.0 apertures Lorentzian wings develop at approximately 20% of peak intensity. The FOS/RD G270H has the narrowest core (FWHM approximately 1 diode) whereas FOS/BL G270H was the widest (FWHM approximately 1.25 diodes). All FOS/BL profiles have broader wings than those in equivalent FOS/RD spectra. The different profiles are attributable to different magnetic and optical focus qualities in the two detectors as well as possible grating alignment differences. The FOS/RD G270H profile most nearly matches the FOS/RD white light profile and the FOS/BL G130H comes closest to the FOS/BL white light profile.

3.9. Observation Timing

The details of precise FOS exposure timing are too complex for a short presentation here. FOS header exposure start times, found in keyword FPKTTIME, contain an uncertainty of at least 0.125 sec. Further, it is not possible to determine the start times of readouts later than the first in a time-series by simple algebraic manipulation of readout times and header keyword entries. Please refer to the *HST Data Handbook* and contact help@stsci.edu if you require timing information more accurate than 0.125 sec.

3.10. Unfinished or Additional Calibration Analyses:

- incorporation of post-COSTAR instrumental polarization correction algorithms into `calfos`
- update dispersion fits to remove possible FGW positional offset systematic errors
- analyze standard star drift scan observations in program 6916 to provide measure of photometric effect of Y-base error as a function of mis-centering and wavelength; also provide measure of granularity changes as function of position perpendicular to dispersion.
- produce superflat-derived flatfields for all pre-COSTAR standard star observation epochs; may improve paired aperture flatfields.
- complete analysis of post-COSTAR dispersed light LSFs
- update FOS ISR 148 description of white-light LSF/PSF

4. FOS Documentation

HST Data Handbook: As noted earlier, the *HST Data Handbook* version 3 volume II for Retired Instruments is intended to be the definitive document on calibration and analysis of FOS data. This edition replaces all previous versions. It contains a technical instrument overview, summaries of important calibration results presented in Instrument Science Reports, and a discussion of the accuracies of the closeout calibration. The document is available in both electronic and hardcopy versions. Please contact help@stsci.edu or refer to the FOS WWW page for additional information.

Instrument Science Reports: FOS Instrument Science Reports (ISRs) contain technical detail pertaining to all aspects of instrument calibration and operation. Typically ISRs are intended to provide low-level and background information that is not frequently required by GOs. All important ISRs are available online for researchers who require this additional information.

Instrument Handbooks: Version 6 (June 1995 - cycle 6) is the best description of the state of the instrument as used in the post-COSTAR era. Version 1.1 (May 1990 - immediately post-launch) provides the best technical description of the instrument available. All other versions of the FOS Instrument Handbook contain no information not found in these two editions and should be considered obsolete.

WWW Resources: The FOS WWW homepage, accessible via the STScI WWW page (<http://www.stsci.edu>) also contains a number of other useful documents and additional items. Information pertaining to any updates to the FOS calibration will be posted on the FOS WWW page first.

5. The FOS Asterism

The FOS functioned for more than five years in HST without a major system failure. Its legacy of more than 20,000 exposures and at least 187 refereed papers (to date) is the tangible result of years of effort by the many individuals in the FOS Investigation Definition Team, Martin Marietta Aerospace Division, Goddard Space Flight Center, STScI, and elsewhere who defined, built, refined, calibrated, and explained the instrument. At the considerable risk of omitting many who are unknown to us, we wish to thank all of the following individuals who have contributed so much of their time and talent over the past 20 years to yield the bounty of the FOS found in the HST Archive:

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