The FOS Scattered Light Model Software

FOS Instrument Science Report CAL/FOS-127 July 1994

Michael R. Rosa*
Space Telescope European Coordinating Facility
European Southern Observatory, D–85748 Garching, Germany
Affiliated to the Astrophysics Division, Space Science Department
European Space Agency

1 Dispersion and diffraction of light in the FOS

The FOS is a single pass spectrometer with blazed, ruled gratings. Both the blue and the red side detectors cover wide spectral ranges. Therefore the FOS is subject to "scattered" light which has its origin primarily in the diffraction patterns of the gratings and the entrance apertures, as well as the micro roughness of gratings due to their ruled surfaces. These limitations are brought about by physical principles. Additional scattering due to contamination of optical surfaces or unbaffeled stray light might be present, although the analysis of laboratory and of in–flight data of the FOS shows that the actual instrument is very close to the performance anticipated from ideal optical surfaces. Therefore, the contamination of observations by scattered light can be predicted with reasonable accuracy.

The program BSPEC is an attempt to model the dispersion and diffraction of light in the FOS with an accuracy sufficient for the estimation of scattered light contamination in standard FOS data. It is a simplified, and therefore much faster, version of the program MSPEC which is a one to one software model of all relevant optical effects.

BSPEC takes as input a spectral distribution of count rates which is dispersed into the most significant spectral orders (eg. -5 to +5) using the equations of blazed gratings and the grating parameters for the various FOS modes. Light from the wing of order zero constitutes a significant component of the scattered light level in the blue part of the first order spectra imaged onto the detector, in particular for the G130H and G190H gratings. The amount of zero order light is determined in BSPEC as the residual flux not being distributed into higher orders. By comparison with the full model of MSPEC it is found that it is sufficient to include orders up to 5. Even for spectra as late as M5 the improvement of including higher orders is below the 10^{-4} level.

The spectral shape in each order is the product of the input spectrum and the blaze function for a given order. The resultant multi–order spectrum is finally convolved with a model of the line spread function (LSF) which represents the effects of diffraction at the finite size aperture, the collimator, the grating and the detector face plate, and includes a flat component to simulate micro–roughness and dust particle scatter.

In order that all significant light is collected and redistributed by both, the grating equations and the convolution with the LSF, the computation has to be performed over a range in diffracted angles much larger than that covered by the actual detector. Both, the red and the blue detector cover the range -1.47 to +1.47 degrees from the grating normal. For the high dispersion gratings zeroes order is located at approximately -7.5 degrees, i.e. the opposite of the incident angle from the collimator. The range -10 to +35 degrees in diffracted angle then covers zero, first and all orders up to 5th.

2 Spectral response, comparison with observations

In practice the correction of observational data for scattered light has to be done before the count rate spectra are transformed into fluxes. BSPEC should therefore be used to produce a model of the data contained in the C4 file intermediate pipeline product. If one ignores sky background the count rate spectra in C4 can be rewritten as

$$C(x) = [\ F(x_\lambda)\ /\ OIVS(x_\lambda) + S(x)\ ]\ /\ FF(x) + B(x) \qquad (1)$$

where C, F, OIVS, S, FF and B are count rate, input flux, the in-orbit determined inverse sensitivity, scattered light, flat field and dark background respectively. The conversion from wavelength to diode domain, x_λ, is given by the grating equation.

The inverse sensitivity curve OIVS converts count rates per diode into energy fluxes incident on HST. A model IVS curve (MIVS) of the combination FOS+HST can be defined as

$$MIVS^{-1} = OTA \cdot MIR \cdot COL \cdot (GBLAZE \cdot GREFL) \cdot DET \cdot \frac{\lambda}{hc} \cdot \Delta\lambda \cdot \frac{\pi}{4} D^2 (1-p) \qquad (2)$$

where OTA, MIR, COL and GREFL are the reflectivities of the HST OTA, the grazing mirror, the collimator and the gratings surface overcoating, DET is the sensitivity of the detector in [counts/photon], GBLAZE the blaze function. The remaining factors convert photon flux per diode resolution element into energy flux per wavelength bin and unit surface area of a telescope with D = 2.4 m diameter and p = 0.138 obstruction.

BSPEC redistributes input data from the wavelength domain into diffracted angles and reshapes the spectrum by the gratings blaze function for each order of interest. Thus in order to compare the output of BSPEC with the observed data (C4 file) the targets model flux spectrum, assumed to be flux(λ) in units of [erg s^{-1} cm^{-2} $Å^{-1}$], needs to be multiplied by a throughput function

$$THR = OTA \cdot MIR \cdot COL \cdot GREFL \cdot DET \cdot \frac{\lambda}{hc} \cdot \Delta\lambda \cdot \frac{\pi}{4} D^2 (1-p) \qquad (3)$$

Note that this function has to be defined and non–negative over the range where the detectors have non–vanishing efficiency, i.e. 1150 Å to 6500 Å or 1500 Å to 9000 Å for the blue and red side respectively. It therefore can not be obtained directly by dividing the blaze function into the in–orbit inverse sensitivity curves (OIVS), since the latter are defined only over the spectral ranges imaged by the detector for a given grating.

Because the reflectivities and detector sensitivities are based on preflight laboratory data, the inverse product of the individual components (1/(THR · GBLAZE) = MIVS is close, but not equal to the in-orbit OIVS. For a direct comparison with observed data therefore the model count rates produced by BSPEC have to be multiplied in addition by a fudge factor, now defined only over the wavelength range imaged by the detector,

$$FUDGE = OIVS/MIVS = (OIVS \cdot THR \cdot GBLAZE)^{-1} \tag{4}$$

GBLAZE can be obtained by a call to BSPEC and is located in array *bfu* (see explanation of OPCODE data arrays in Appendix B).

The procedure is described step by step below, using the example of a solar type target (16 Cyg B) which also served to produce the figures described in the Appendix C to the FOS Instrument Handbook, V 5.0, May 1994. Grating constants and suggested values for free parameters are given in in the Appendix A.

3 Example calculation

For illustration let the model target spectrum be the model atmosphere appropriate for the Sun (Kurucz 1993, priv. comm), observed in the FOS BLUE G190H mode through the 1.0 arcsec round aperture, pre–COSTAR. First we prepare our flux input using the conversion factor THR, which is obtained with the task *countspec*. We now have to create a work array (an SDAS table) which will hold the various intermediate steps and the final model observation.

The detector covers a range of ± 1.47 degrees of the diffracted angle, corresponding to the wavelength range 1573 Å to 2330 Å. We want to include orders -1 to +5 up to the central wavelength, i.e. 1900 Å. From equation 1 we get limits for the diffracted angle of -15 to +33 degrees. The observed data have a resolution of 1.5 Å / diode or 0.38 Å per pixel at 1900 Å in first order. Our input spectrum is sampled at intervals of 2 Å only. For the present purpose let us compute a model with a sampling that matches that of the C4 data. From the Appendix we obtain a resolution of 0.0059 degrees per diode. We thus need a sampling in diffracted angle of 0.001475 degrees, or 32547 data points to cover the range -15 to +33 degrees. Our input spectrum is finally defined over the range 0 to 20000 Å but we will include only the range 1100 to 7000 Å.

All other numerical parameters are obtained from the tables in the Appendix, and we have the following parameter set for the call to BSPEC

- groove separation = 1.458 [mu]
- effective number of grooves = 23400
- blaze angle = 3.75 [deg]
- incident angle = 7.716 [deg]
- lowest non-negative order to include = 0
- highest non-negative order to include = 5 (this will also compute -5 to -1)
- fall off of Voigt LSF = 0.003
- width of Voigt LSF = 0.01
- flat component of LSF = 1.5E-06
- lower limit of input spectral range = 1100 Å
- upper limit of input spectral range = 7000 Å
- operation code = 0 (the default)

After execution the result (array *ablg*) has to be multiplied with the fudge factor FUDGE, and the background (from the .c7 file) needs to be added in order to compare directly with the .c4 data (see Figure C2 in Appendix C of FOS Instrument Handbook, V 5.0, May 1994).

Appendix A

Table 1: **FOS grating constants**. Groove separations are from FOS-UCSD-SE01C *Instrument Description and User Handbook for the FOS*, Draft, October 1986. Effective groove numbers are computed using the grating dimensions of 43.5 mm diameter. Incident angles are computed using the central wavelengths from Table 1.1.1 of the FOS Instrument Handbook V5.0, May 1994. Blaze angles are obtained by fitting model IVS curves including the blaze function to the observed IVS curves (M.R. Rosa, CAL/FOS, in preparation July 1994). Low res gratings and prisms – data not yet finalized, code for inverse dispersion relation for prism not yet included.

Grating	Groove width	Effective	Blaze angle [deg]		Incident angle [deg]	
	[μ]	# of grooves	Blue	Red	Blue	Red
G130H	1.000	34200	3.78	—	7.766	—
G190H	1.458	23400	3.75	3.74	7.716	7.684
G270H	2.083	16400	3.65	3.65	7.643	7.649
G400H	3.055	11200	3.80	3.80	7.610	7.607
G570H	4.444	7700	3.80	3.80	7.430	7.426
G780H	5.834	4900	—	3.80	—	7.701
G160L	6.944				(3.475)	(3.475)
G650L	25.00				(3.475)	(3.475)
PRISM	—					

Table 2: **Additional constants and parameters for FOS scattered light model**

Description	Default value	Typical range	Unit
Curvature radius of grating	1000	—	mm
Angle subtended by diode	0.0059	—	deg/diode
Orders to include	0 - 3	0 - 5	
Diffracted angles	-10 – +30	-15 – +45	deg
Range of wavelengths	all	1150 - 9000	Å
LSF fall off	0.003	0.002 - 0.004	deg^{-1}
LSF core width	0.01	0.005 - 0.015	deg^{-1}
Flat component of LSF	1.5E-06	5E-07 – 5E-06	—

Appendix B

Input/Output Data arrays and operation code

Input data consist of a 2 column table storing the model targets blaze–free count rate spectrum as a function of wavelength of the model target in columns *wave* and *flx*.

Output data are stored in the work–table. The independent used is *angle*, the diffracted angles. Sampling is determined by the users choice of this independent. Column *gwav* holds the first order wavelengths [Å] BSPEC assigns to these diffracted angles. There are two columns for intermediate storage of the slow and fast phases at the grating, called *phase1* and *phase2*.

Depending on **OPCODE** BSPEC proceeds to fill the following output arrays:

1. Fill *benv* with the $\pm$ first order dispersed input flux; fill *blg* with the input flux dispersed into the orders requested and weighted by the blaze function.
2. Compute a model of the LSF, column *apd*.
3. Convolve the dispersed spectrum in *blg* with the LSF in *apd* and store in final output array *ablg*.
4. For test purposes only evaluate the blaze function for orders different from first and store into *bfu*.

OPCODE = 0, the default, executes steps 1 through 3.