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Time Dependent Trace Angles for the STIS First Order Modes

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ABSTRACT

Single rows in STIS rectified spectral images and spectral extractions made with small extraction boxes are being analyzed in science programs where the highest obtainable spatial resolution is needed. Here we address a problem that has limited the accuracy of these data products: the spectral traces in the reference files often do not have the same tilt as those in the science exposures. By analyzing data for the most commonly used first order spectral modes, we have determined that the traces have been systematically rotating over time. We have delivered spectral trace reference files that apply the calibrated rotation to the most commonly used modes. We have also produced a PyRAF routine, MKTRACE, that measures the tilt of the trace in a science image and produces a corrected trace reference file for that image. Using corrected traces, we have analyzed the flux calibration of L grating spectra extracted with small boxes. We find substantial errors in the spectral shape of small-box extractions of G430L spectra due to uncalibrated systematic wavelength-dependent variability of the point spread function, which becomes broader at long wavelengths as it becomes narrower at short wavelengths.

1. Introduction

The spectral trace is the track followed by the spectrum of a point source across a raw spectral image. The accuracy of the characterization of spectral traces is most critical when single rows are to be analyzed in rectified spectral images (sx2 or x2d images from the STScI pipeline). For extracted spectra (sx1 or x1d tables), the accuracy of the applied trace becomes increasingly important as the size of the extraction box decreases. (See the STIS Data Handbook for descriptions of the pipeline data products and calibration reference files.)

STIS spectral extractions and spectral image rectification are performed using spectral trace reference files. A trace reference file (1dt.fits) contains a series of traces that span the detector for each combination of grating and central wavelength setting. Interpolation is used to obtain traces at positions between those in the file. Trace reference files were initially created for STIS using ground-based measurements. Most updates to these files were made in August 1998 using in-flight calibration data obtained by June 1997, a few months after the installation of the instrument. Errors in the traces were often evident in rectified spectral images produced by the pipeline, since individual rows in these images are sensitive to errors of a fraction of a pixel. It was not known if deviations from the reference file traces were random or systematic with time. As part of the STIS close-out plan, traces have been derived from exposures of stars and other compact sources and examined as a function of observing date for the most commonly used combinations of gratings and central wavelengths (Section 2). Because time dependence was found in the tilt of the traces on the detectors, reference files have been generated with time evolution for the most commonly used modes (Section 3), and a trace-rotating tool has been added to PyRAF (Section 4). Trace shapes were also rederived in a uniform manner for the most commonly used modes (Section 3). The reference files that contain new evolving traces will be referred to as the new files, and the files with only static traces that preceded them will be designated as the old files.

2. Evolution of Spectral Traces over the Lifetime of STIS

2.1 Measurement of Traces

To derive traces for the analysis, a robust code was developed to process the spectral images of stars and of slightly resolved targets, which were needed to fill out the sample for some modes. A Gaussian fit was made to the cross-dispersion profile in each column of the observed spectral image (flt or crj file). The resulting trace, consisting of the location of the peak of the Gaussian in each column, was found to be vulnerable to the undersampling of the point spread function (PSF) along the slit. Traces produced this way had undulations whose phase depended on the centering of the trace within a pixel. To stabilize the Gaussian fitting and eliminate this effect, boxcar smoothing of 3 pixels was performed along columns before making the fits. The trace was then smoothed along the dispersion direction using a Gaussian of 10 pixels width. Finally, it was zeroed at the central column (513 for a width of 1024 pixels). Refinements were made to handle extended background (subtracting off the median background before Gaussian fitting) and aberrant points in the trace (replaced by the local median before smoothing in the dispersion direction).

The traces are nearly linear, but are not perfectly aligned with the X axis of the detector. The tilt of each trace on the detector was measured by fitting a straight line to it. For the low resolution L gratings, good traces were obtained from well-exposed spectral images of standard stars taken in calibration programs. For the medium resolution M modes most commonly used by observers, the science exposures constituted the bulk of

the archival data. Some of the exposures were unsuitable for making traces because of spatial and velocity structure, and some exposures had poor signal-to-noise. The rms of a linear fit to the derived trace was found to be a good discriminator of useable traces. For each M mode, analysis was performed on traces for which the rms of the fit was less than a few times the minimum value.

2.2 CCD L Modes

Spectral traces at the center of the detector were derived for the CCD L gratings from exposures of the standard star AGK+81D266 (type SD0). The observations were made as part of the STIS CCD sensitivity monitoring calibration programs (7672, 8418, 8856, 8914, 9627, 10030) using the 52X2 aperture, and span most of the operational lifetime of STIS. Figure 1 shows the traces derived for G430L, which span a range of angles. The old reference file trace at the center of the detector (derived from the CCD trace file 12j0137so_1dt) is also shown in Figure 1, and does not quite match any of the observed traces. Most of the trace reference files were made from data taken before an instrument commanding change was made on 21 July 1997 (MJD 50650). Beyond that date, the three cylinders that position the gratings to selected wavelength settings were commanded to a slightly different set of positions, resulting in slight changes in the position and angle of the spectrum on the detectors. Almost all STIS science observations were made after the commanding change.

The tilt of each trace in Figure 1 was measured by fitting a straight line to it. The range in Y spanned by each line is plotted as a function of observing date in Figure 2. (The range is defined as Y(1024)-Y(1), so that a positive slope gives a positive range.) This figure shows that the trace has rotated steadily clockwise with time, changing its range in Y by about half a pixel across the 1024 pixels in X. Clearly, the tilt of the trace depends mostly on time, with much smaller random deviations superimposed on the systematic change. The points are distributed about the plotted linear fit with an rms of 0.03 pixels. The trend is not clearly related to the complex thermal history of the CCD detector, including the change in temperature control necessitated by the switch to side 2 electronics in July 2001.

Similar analysis has been performed for the gratings G230LB and G750L, with similar results, as shown in Figures 3 to 6. (For G750L, fringing clearly affects the derived traces at the red end of the wavelength range.) For all three of the CCD L gratings, the trace has rotated clockwise, changing its range in Y by about half a pixel over a period of seven years. (Figures 2, 4, and 6 have been plotted with the same Y scale to facilitate comparison.) The accumulating difference of the observed traces from the old reference file traces noticeably affects rectified spectral images, causing the location of the peak flux in a column to shift by about half a row from one end of the spectrum to the other in the latest observations. The magnitude of the slope of the linear fit to the evolution, expressed in degrees of rotation per year (Section 3), is 0.0031+/-0.0003 for G230LB, 0.0041+/-0.0001 for G430L, and 0.0037+/-0.0003 for G750L. The rotation rates for G230LB and G430L thus formally differ at the 3 σ level.

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Figure 1: Traces at the center of the detector for G430L(4300) measured from 39 exposures of a standard star spanning the STIS lifetime (green lines) and the old reference file trace (black line).



Figure 2: Evolution of the tilt of the trace for G430L(4300). The range in Y of a linear fit to each trace displayed in Figure 1 is plotted as a function of observing date. A linear fit to the evolution is shown.



Figure 3: Traces at the center of the detector for G230LB(2375) measured from 39 exposures of a standard star spanning the STIS lifetime (blue lines) and the old reference file trace (black line).



Figure 4: Evolution of the tilt of the trace for G230LB(2375). The range in Y of a linear fit to each trace displayed in Figure 3 is plotted as a function of observing date. A linear fit to the evolution is shown.



Figure 5: Traces at the center of the detector for G750L(7751) measured from 39 exposures of a standard star spanning the STIS lifetime (red lines) and the old reference file trace (black line). Fringing affects the derived traces at long wavelengths.



Figure 6: Evolution of the tilt of the trace for G750L(7751). The range in Y of a linear fit to each trace displayed in Figure 5 is plotted as a function of observing date. A linear fit to the evolution is shown.

To set limits on the effects of signal to noise on trace measurement, we located a file of cr-split exposures with far lower signal to noise than the exposures used in the evolution analysis: o8v204090, which has four 4-second exposures of GD71 taken with G230LB. Most of the G230LB exposures used in the evolution analysis have from 3000 to 41500 electrons per column. The flt images in o8v204090 each have only 15 to 262 electrons per column, yet the rms in the range of their traces about the mean is only 0.04 pixels. The mean range for these 4-second exposures differed from the range of the immediately following 45 sec exposure, o8v2040a0, by only 0.015 pixels. The error due to noise in measuring the range of the trace should be much smaller than 0.04 pixels for the well-exposed images used to make the evolution plots. Slight differences in each positioning of the grating and small changes in the optical path over time must therefore be predominantly responsible for the scatter in these plots.

2.3 CCD M Modes

Only a few calibration exposures of standard stars were made with the most commonly used CCD M modes (G750M with CENWAVE 6581, 6768, 8561), and most of these were performed during the first two cycles of STIS operations. Long-slit exposures (apertures 52X0.1, 52X0.2, 52X0.5, 52X2) were therefore collected from GTO and GO programs as well as calibration programs, excluding moving targets. As explained above, the rms of a linear fit to the derived traces was used to select the best traces, which were generally obtained from exposures of the most compact sources with good signal to noise and few columns affected by spatially extended emission lines. Analysis was performed on traces for which the rms of the fit was less than a few times the minimum value for the sample, with the cutoff value adjusted to achieve an adequate sample size while still excluding low quality traces. The sample with CENWAVE 6768 was by far the largest sample, due to a series of programs to monitor Eta Carinae.

The trace analysis for G750M(6768) revealed a feature not found for the CCD L gratings: there are two parallel tracks on the trace tilt evolution plot, separated by 0.4 pixels (Figure 7). There are more occurrences of traces on the lower track (57) than on the upper track (21). As for the L gratings, each track corresponds to a gradual clockwise rotation of the trace, with a change in Y-range of nearly half a pixel over the operational lifetime of STIS.

The two bands of traces corresponding to the two tracks are shown in different colors in Figure 8, after subtraction of a line of Y-range -7.5 so that the differences in angle can be seen more easily. The old reference file trace (black in the figure) is close to the earliest upper-track traces, and is in error by 1 pixel in Y-range for the latest lower-track traces. Placement on one track or the other does not appear to depend on any observational parameters. Even for two exposures of the same target taken within the same orbit, one exposure can have a trace on the lower track and the other on the upper track. This was the case for the pairs o8gm120i0 and o8gm120k0 (separated by 12 minutes), o8gm520y0 and o8gm520z0 (separated by 9 minutes), and o8ma920j0 and o8ma920k0 (separated by 9 minutes). In all of these cases, intervening exposures were



Figure 7: Evolution of the tilt of the trace for G750M(6768). The range in Y of a linear fit to each trace is plotted as a function of observing date. Two linear fits to the evolution have been made (to the squares and triangles) since two tracks separated by 0.4 pixels in range are clearly evident.



Figure 8: Traces at the center of the detector for G750M(6768) measured from 78 exposures of compact targets spanning the STIS lifetime (colored lines) and the old reference file trace (black line). The (57 red, 21 blue) lines are on the (lower, upper) evolutionary track in Figure 7. A line of slope -0.0073 (corresponding to a drop of 7.5 pixels across the detector) has been subtracted from the traces so that their relative tilt can be seen.



Figure 9: Shifts in X and Y (pixels) from the reference position for exposures with traces on the lower (square) and upper (triangle) evolutionary tracks for G750M(6768) shown in Figure 7.

taken at a different central wavelength setting, so the grating was moved by the Mode Select Mechanism (MSM) between the earlier and later exposures at CENWAVE 6768. The positioning of the grating thus has a duality for this central wavelength setting in addition to the small random non-repeatability that is characteristic of all modes.

Slight differences in the positioning of the grating result in small differences in the X,Y positioning of the spectrum on the detector. The offsets from a reference position are measured from the associated wavecal image (wav), using the emission lines to determine the offset in the dispersion direction (keyword SHIFTA1) and the edges of occulting bars to determine the offset in the cross-dispersion direction (SHIFTA2). (Inaccuracies in target acquisition or tracking are thus not included in the measurement, but imperfect MSM repeatability and thermal distortions in the optical bench are.) The X,Y offsets are correlated with the tilt of the trace. For the co-orbital pairs of exposures named above (o8gm120i0 and o8gm120k0, o8gm520y0 and o8gm520z0, o8ma920j0 and o8ma920k0), the change in the Y-range of the trace between exposures was -0.34, -0.40, and -0.38 pixels, the change in SHIFTA1 was -2.01, -2.17, and -2.02 pixels, and the change in SHIFTA2 was -1.34, -1.29, and -1.39 pixels, respectively. The offset coordinates (SHIFTA1, SHIFTA2) are plotted in Figure 9 for the 66 exposures in the previous two figures that had an associated wavecal. As in Figure 7, exposures on the lower evolutionary track are represented by squares, and those on the upper track are represented by triangles. These independently measured offsets are predictive of whether the trace in the science image will fall on the low or high track.

Only single evolutionary tracks were found for G750M(6581) and G750M(8561).



Figure 10: Traces at the center of the detector for G750M(6581) measured from 60 exposures of compact targets spanning the STIS lifetime (red lines) and the old reference file trace (black line). A line of slope -0.0074 (corresponding to a drop of 7.6 pixels across the detector) has been subtracted from the traces so that their relative tilt can be seen.



Figure 11: Evolution of the tilt of the trace for G750M(6581). The range in Y of a linear fit to each trace displayed in Figure 10 is plotted as a function of observing date. A linear fit to the evolution is shown.



Figure 12: Traces at the center of the detector for G750M(8561) measured from 35 exposures of compact targets spanning the STIS lifetime (red lines) and the old reference file trace (black line). A line of slope -0.0056 (corresponding to a drop of 5.8 pixels across the detector) has been subtracted from the traces so that their relative tilt can be seen.



Figure 13: Evolution of the tilt of the trace for G750M(8561). The range in Y of a linear fit to each trace displayed in Figure 12 is plotted as a function of observing date. A linear fit to the evolution, excluding the most deviant point, is shown.



Figure 14: Traces at the center of the detector for G230LB (blue), G430L (green), G750L (dashed red), and G750M with CENWAVE 6581 (red), 6768 (red), and 8561 (dashed red). A linear fit has been subtracted from each trace to align the traces so that their shapes can be compared. The dashed lines represent traces affected by fringing.

Figure 10 shows traces measured from 60 exposures of compact sources made using G750M(6581), along with the old reference file trace, relative to a line of Y-range -7.6. Figure 11 shows the evolution of the tilt of the trace for this sample. The reference file trace matches the traces of the earliest exposures, and the trace rotates clockwise with a change in Y-range of nearly half a pixel. Figures 12 and 13 are the analogous plots for 35 exposures made of compact sources with G750M(8561). In Figure 12, the traces have been plotted relative to a line of Y-range -5.8. Fringing adds fine structure to the derived traces at this wavelength. As before, the trace rotates clockwise with a change in Y-range of nearly half a pixel, but the old reference file trace is under-rotated for even the earliest traces in the sample.

2.4 Trace Shapes for the CCD L and M Modes

The shapes of the traces for the CCD L and M modes were found to be invariant with time, grating, and central wavelength. Only the tilt of the trace depends on these parameters. This is shown in Figure 14, where the trace at the center of the detector minus its linear fit is plotted for each of the most commonly used CCD modes. (The trace shown for each mode is actually the median of the traces in the evolution study sample for that mode, taken after subtracting the linear fit from each trace to rotate the traces to the same angle.) Traces for different modes can thus be used interchangeably if rotated to the appropriate angle.

2.5 FUV L Mode

The FUV-MAMA has a repeller wire which repels electrons emitted away from the microchannel plate back into the channels to increase the quantum efficiency of the detector. (See the description of the MAMA detectors in Chapter 7 of the STIS Instrument Handbook.) This wire casts a shadow on the detector. To avoid placing first order spectra in this shadow, the Mode Select Mechanism was initially commanded to use settings that projected the spectrum of a target at the nominal position to a location 3 arcsec above the center of the detector. The FUV-MAMA dark current is low, but a somewhat higher and variable current at the upper left of the detector could be a problem for some observations. (See the description of the MAMA darks in Chapter 7 of the STIS Instrument Handbook.) Starting on 15 March 1999, the MSM settings for the first order MAMA modes were changed to place spectra 3 arcsec below the center of the detector, thus avoiding both the repeller wire shadow and the region of higher dark current.

Exposures made with G140L in the MAMA sensitivity monitoring calibration programs (7673, 8424, 8857, 8919, 9628, 10033) were used to investigate the traces. The DA white dwarf GRW+70D5824 was observed through the 52X2 slit. The sample was divided into two time periods, before and after the MSM setting changes on 15 March 1999. In the early sample (18 exposures), spanning 16 September 1997 to 8 March 1999, the spectrum was placed at row 640 in lo-res (low resolution) coordinates. In the late sample (45 exposures), spanning 11 April 1999 to 8 June 2004, the spectrum was placed at row 384.

The traces for G140L are strongly curved near the short and long wavelength ends of the spectrum. The flux is very low in the broad Ly α absorption line (centered on column 160) in the exposures of GRW+70D5824, and at the ends of the spectrum where the sensitivity is low. The tilt of the traces was therefore measured using a weight of 1 for columns 200 to 900 and 0 elsewhere to stabilize the linear fits.

The measured traces and old reference file trace (from mam152900_1dt) for the early sample and the Y-range of the linear fits as a function of date are shown in Figures 15 and 16, respectively. No fit to the evolution of the tilt has been made over this short time span since the scatter in the tilt obscures any time dependence. The traces and tilt evolution for the later sample are shown in Figures 17 and 18, respectively. The trace has rotated counter-clockwise over this five year period, changing its Y-range by 0.25 lo-res pixels. The old reference file trace is under-rotated even for the earliest exposures at this MSM setting.

2.6 NUV L Mode

As for G140L, observations of GRW+70D5824 made as part of the MAMA sensitivity monitoring calibration programs (7673, 8424, 8857, 8919, 9628, 10033) were used to investigate the traces for G230L. The sample consists of 64 exposures made through the 52X2 slit with the target centered on the detector. The traces for this grating are the most strongly tilted of the traces analyzed in this study, dropping by about 18.5 lo-res pixels



Figure 15: Traces for G140L(1425) measured from 18 exposures of a standard star observed at MOFFSET2=124 (row 640 in lo-res pixels; purple lines) and the old reference file trace (black line). The feature at column 160 is due to lack of signal.



Figure 16: "Evolution" of the tilt of the trace for G140L(1425) before 15 March 1999. The range in Y of a weighted linear fit to each trace displayed in Figure 15 is plotted as a function of observing date. No time dependence is seen over this short time range.



Figure 17: Traces for G140L(1425) measured from 45 exposures of a standard star observed at MOFFSET2=-134 (row 384 in lo-res pixels; purple lines) and the old reference file trace (black line). The feature at column 160 is due to lack of signal.



Figure 18: Evolution of the tilt of the trace for G140L(1425) after 15 March 1999. The range in Y of a weighted linear fit to each trace displayed in Figure 17 is plotted as a function of observing date. A linear fit to the evolution is shown.



Figure 19: Traces at the center of the detector for G230L(2376) measured from 64 exposures of a standard star spanning the STIS lifetime (blue lines) and the old reference file trace (black line). A line of slope -0.0181 (corresponding to a drop of 18.5 lo-res pixels across the detector) has been subtracted from the traces so that their relative tilt and structure can be seen.



Figure 20: Evolution of the tilt of the trace for G230L(2376). The range in Y of a weighted linear fit to each trace displayed in Figure 19 is plotted as a function of observing date. Two linear fits to the evolution have been made (to the squares and triangles), before and after MJD 51700.

as they cross the detector. The traces relative to a line of this tilt are shown along with the old reference file trace (from 13m14384o_1dt) in Figure 19. The tilt of the traces was measured using a weight of 1 for columns 40 to 960 and 0 elsewhere to stabilize the linear fits, since the traces are highly non-linear at the ends. The measured Y-ranges of the fits are shown as a function of date in Figure 20. The tilt has changed very little over the 7 year time span, but the scatter is sufficiently small (0.03 lo-res pixels relative to the fit lines) that a systematic change can be seen. A two-segment linear fit indicates that the magnitude of the Y-range increased by about one lo-res pixel over the first 3 years (clockwise rotation), then decreased by about half a lo-res pixel over the next 4 years (counter-clockwise rotation). This behavior does not appear to be related to the thermal history of the detector (P. Goudfrooij and C. Proffitt, private communication).

3. New Trace Reference Files

The spectrum trace table (1dt.fits) to be used in processing a science image is specified in the SPTRCTAB header keyword of the science data file header. For a given grating (OPT_ELEM) and central wavelength setting (CENWAVE), a sequence of rows in the table contains a set of traces that span the detector. A vector (A2DISPL) gives the Y-position of a trace in each column of the detector relative to the Y-position (A2CENTER) at the central column (A1CENTER). Two new parameters have been introduced to the reference file to define the evolution of the tilt of the trace: DEGPERYR gives the rate of rotation of the trace on the detector in degrees per year and MJD gives the date for which the reference file trace needs no rotation. CALSTIS (Version 2.23, 06 October 2006) has been modified to use these parameters to rotate the traces to the orientation needed for the date of the exposure being processed. This version of CALSTIS was included in the release of STSDAS Version 3.6 on 13 November 2006. For OPT_ELEM/CENWAVE combinations not included in this study, DEGPERYR has been set to zero in the reference files and no rotation is performed.

New sets of traces were produced for the modes with measured evolution using the data listed in Table 1. In each program, the target was stepped along the 52X2 slit in the cross-dispersion direction to produce a series of spectra that span the detector. A single star was observed with the G140L and G230LB gratings, so that the number of traces produced (20 and 33, respectively) equals the number of exposures. For the G230L exposures, the slit was aligned with three bright stars spaced at intervals of 6 arcsec in the cluster NGC346-368, allowing 23 traces to be produced from 8 stepped exposures. An 11 node spline fit was made to each derived trace to produce the reference file trace.

It was shown in Figure 14 for the CCD L and M gratings that, while the tilt of the trace depends on the grating, central wavelength, and date, the shape at a given Y-position (A2CENTER) on the detector is invariant. The set of traces made from the G230LB exposures were therefore used to make reference file traces for G230LB(2375), G430L(4300), G750L(7751), G750M(6581), G750M(6768), and G750M(8561). The full set of G230LB traces was rotated as needed for each mode to achieve an orientation

Grating	Program	Exposures	Date	Target	No. of	No. of
					Exposures	Traces
G140L	7937	o530010*	06 Feb 1999	GD71	20	20
G230L	7667	o46j010*	02 Sep 1997	NGC346-368	8	23
G230LB	7665	o45p020*	13 Feb 1998	HD120315	33	33

Table 1: Data used to make traces for reference files

at a specified MJD in agreement with the plots of Y-range at the center of the detector versus date (Figures 2, 4, 6, 7, 11, 13). The more heavily populated lower evolutionary track in Figure 7 was used for G750M(6768). The slope of the fits in the evolution plots was converted to DEGPERYR.

A change in the MSM settings for a given mode produces a change in the tilt of the traces. The traces for G140L(1425) were rotated to the average orientation seen in Figure 16 for a reference file to be applied to exposures made up to 14 March 1999, with DEGPERYR set to zero. A reference file for exposures taken after that date was made by rotating the traces to a later date in accord with Figure 18 and converting the slope of the fit to DEGPERYR. Finally, the traces made for G230L(2376) were given an MJD and DEGPERYR appropriate to the first segment of the fit in Figure 20 for a reference file for data taken through MJD 51700 (4 June 2000), and an MJD and DEGPER year appropriate to the second segment of the fit for a reference file for data taken after that date.

Reference file	USEAFTER	Detector	Grating	No. of	DEGPERYR
	Date		(CENWAVE)	Traces	
q81145030_1dt	01 Oct 1996	FUV	G140L(1425)	20	0.0000
q81145040_1dt	14 Mar 1999			20	-0.0030
q81145010_1dt	01 Oct 1996	NUV	G230L(2376)	23	+0.0024
q81145020_1dt	05 Jun 2000			23	-0.0007
qa31608go_1dt	01 Oct 1996	CCD	G230LB(2375)	33	+0.0031
			G450L(4300)	33	+0.0041
			G750L(7751)	33	+0.0037
			G750M(6581)	33	+0.0041
			G750M(6768)	33	+0.0047
			G750M(8561)	33	+0.0053

Table 2: New reference files with new trace shapes and time-dependent rotation for the indicated CENWAVEs

Five 1dt reference files with evolution parameters were delivered on 22 August 2006: two each for the different time ranges for G140L and G230L and one for the CCD modes. Minor changes to the CCD traces were made in a file delivered on 3 October 2006. Table 2 gives a summary of the information in the new reference files:

the USEAFTER date, the detector, the gratings and central wavelengths of the modes with new traces and calibrated tilt evolution parameters, the number of traces spanning the detector for the updated mode, and the rate of rotation of the traces on the detector, DEGPERYR, in degrees per year with clockwise rotation positive. A science data file will use the reference file for its observing mode with the latest USEAFTER date that precedes its own exposure date.

4. New Software to Rotate Traces

Some science exposures will not be well fit by the reference file traces, either because time evolution of the tilt has not been included in the new reference files for that grating and central wavelength, or because the needed trace lies on the other track of a dual track evolution (e.g., for G750M(6768)), or because of an unusually large random deviation in the tilt. For those cases, we have provided a PyRAF routine to measure the needed rotation of the trace using selected portions of the science spectrum and to produce a new reference file with rotated traces. This routine, MKTRACE, was included in STSDAS Version 3.6 released on 13 November 2006.

MKTRACE begins by generating a trace from the science file (flt or crj) following the prescription given in the section "Measurement of Traces". The trace is obtained from a 40-row subarray centered on the nominal Y position of the target in the aperture or on a Y position specified by the user. The two reference file traces bracketing the computed science trace center are extracted (without rotation) from the trace table and interpolated to give a trace at the same location on the detector as the science trace. The correction to the tilt of the interpolated trace is computed as the difference between weighted linear fits to the interpolated trace and to the science trace. The weights are set to 1 by the user for ranges of column numbers that are useable in the science trace, and are otherwise set to 0. The user can thus exclude regions of the spectral image with poor signal-to-noise or complex spatial and velocity structure. Fits format files of the science trace, the interpolated reference file trace, and the linear fits are provided for the user to examine to determine the appropriate weighting and to evaluate the quality of the fit. The computed correction to the tilt is applied to all traces in the trace table with that particular OPT_ELEM and CENWAVE, and DEGPERYR is set to zero so that no further rotation will be performed by CALSTIS. The updated trace table is written out to the current directory, and SPTRCTAB in the primary header of the science file is changed to the name of this new table. CALSTIS or its components can then be run on the science file and will use the new trace table.



Figure 21: The FWHM (pixels) of Gaussian fits to each column of the flt or crj image of a star made with gratings G140L (violet line), G230L (blue line), and G430L (green line). The FWHM obtained after boxcar smoothing by 3 pixels along columns is also shown for G230L (dashed blue line). All lines have been boxcar smoothed by 11 pixels. The feature at column 165 for G140L results from a lack of signal.

5. Effects of the New Calibration on Data

5.1 Limitations Imposed by Under-sampling the Spatial PSF

Errors in the applied traces are most consequential for single rows in rectified spectral images and for extractions made with small extraction boxes. The size of the PSF relative to the pixel size of the detector limits the size of the extraction box that can be used to obtain an accurate spectrum of a spatially compact component. When the PSF is undersampled along the slit, the artifacts resulting from the interpolation of the undersampled profile can be reduced by using a larger extraction box.

Figure 21 shows the FWHM of the spatial profile in each column in the spectral images of stars made with gratings G140L, G230L, and G430L. Each exposure was taken from the sample of calibration exposures used to measure the evolution of the tilt of the trace for that grating. Each exposure was chosen as representative of the sample because it has the median value of the FWHM at the central column for that sample. The sample of exposures with the target centered low on the detector was used for G140L. The FWHM was measured by fitting a Gaussian to each column in the unsmoothed flt or crj image. The resulting function, FWHM versus column number, was then smoothed with a running average over 11 pixels. The G140L image has the best spatial sampling, especially at the short wavelength end, where the FWHM spans 4 lo-res FUV-MAMA

pixels. (The measurements are poor around column 165 and below column 40, where the signal goes to zero. The plot begins at column 40.) The effects of undersampling on the Gaussian fits are conspicuous in the periodicity of the fluctuations in the FWHM function for G230L, especially at the long wavelength end, where the FWHM is about 2.3 lo-res NUV-MAMA pixels. Each fluctuation period in the FWHM function corresponds to the distance in the dispersion direction over which the trace drops by one row. If the G230L image is boxcar-smoothed by 3 pixels along columns before the Gaussian fitting is done, the dashed line in Figure 21 is the resulting smoothed-FWHM function. The same preliminary smoothing that removed undersampling artifacts from the traces thus also removes them from this width metric, which makes it a useful metric for analysis. The spatial PSF for G430L is even more undersampled than that for G230L, but the nearly flat trace ensures that the PSF is sampled nearly the same way by the pixels in each column. The undersampling therefore modulates the measured FWHM by nearly the same factor in each column, producing a nearly featureless FWHM function in Figure 21. (G230LB has a similar FWHM function to G430L, while the flux profiles for G750L are contaminated by a halo of scattered light.)

In the following sections, we will first examine single rows of a rectified spectral image of a star made with grating G140L, which gives the best sampling of the spatial PSF. We will then examine spectral extractions using different box heights for images made with G430L, where extraction boxes of 3 or greater are needed to diminish the artifacts of spatial undersampling. By limiting the effects of undersampling on the spectrum, we can more clearly see the differences due to applying the old and new traces. We will show that, when the new traces are applied, wavelength-dependent variability in the spatial PSF becomes the limiting factor in the accuracy of the shape of extracted spectra.

5.2 Spectral Images

If the PSF is independent of wavelength, the single-row spectra of a star in a well sampled and properly rectified spectral image will be very similar except for a scaling factor determined by where they lie on the spatial profile of the PSF. If the width of the spatial PSF gradually varies across the spectrum (Figure 21), the single-row spectra will be modulated by a function that changes slowly with wavelength. This is the case for spectral images made with G140L. Figure 22 shows rows from the x2d image of the star GRW+70D5824 observed with G140L(1425) through the 52X2 aperture (program 10033, exposure o8v503010). This was the last G140L exposure made in the sensitivity monitoring program, on 08 June 2004. The old spectral trace file (mam152900_1dt) was used for the upper panel in the figure, and the new file with date-dependent rotation (q81145040_1dt) was used for the lower panel. The parameter SHIFTA2 was adjusted to center the star between two rows in the rectified image. For a spatially symmetric PSF, the central two rows should be similar to each other, and the next rows out should be similar to each other, in both amplitude and shape. This has been achieved with the new trace reference file. The old reference file, which is most incorrect for the most



Figure 22: The central 4 rows in the rectified spectral image of a star observed with the G140L grating. The old (upper panel) and new (lower panel) trace reference files have been used. Counts per pixel have been converted to surface brightness (cgs units).

recently taken data, produces substantial errors in the single-row spectra. These errors can be consequential for the analysis of components in spatially and spectrally complex sources where the highest spatial resolution is needed.

5.3 Extracted Spectra

The CALSTIS pipeline extracts the spectrum of a target at the default location using an extraction height of 11 pixels for the MAMA detectors and 7 pixels for the CCD detector. The photometric calibration includes wavelength-dependent adjustments for slit losses and light beyond the extraction box based on the assumption that the target is a point source. The STSDAS routine x1d, based on a component of CALSTIS, can be used to produce extractions with different extraction heights. Smaller extraction heights are useful for isolating compact components from contaminating emission from other sources. The smallest extraction height with calibrated corrections for light loss is 3 pixels. The improvement in extracted spectra achieved by using the time-dependent trace file is shown in Figure 23 for the last six exposures of AGK+81D266 made with G430L in the CCD sensitivity monitor programs (exposures o8u203030, o8u204030, o8u205030, o8u206030, o8u207030, o8u208030 in program 10030). These observations were made over the eight months ending with the suspension of STIS operations in August 2004, so will need the largest corrections to the old trace file. For each exposure, spectra with extractions of height 3, 5, and 7 pixels were made using the old



Figure 23: Spectral extractions for 6 exposures of a standard star made with grating G430L using extraction box heights of 7, 5, and 3 pixels (top to bottom panels) divided by an extraction using a box height of 11 pixels to normalize out the stellar spectrum. The old trace reference file was used on the left and the new file on the right. Each exposure is represented by a different color.



Figure 24: The same as Figure 23, except that each curve has been divided by its median to facilitate the comparison of spectral shapes.

trace file 12j0137so_1dt and the new evolving trace file qa31608go_1dt. Each of these spectra was divided by an 11 pixel extraction made with the new trace file to show the discrepancy between the narrow box extraction and the best wide box extraction. Box-car smoothing by 11 pixels was applied in the dispersion direction to improve the signal to noise. Figure 23 shows the normalized extractions made with the old trace file on the left and those made with the new evolving trace file on the right. Spectra with the default extraction box of 7 pixels show changes of only a few tenths of a percent at most, but the smaller extraction boxes give increasingly poor results for the older trace file. The normalized spectra generally become increasingly bowed and mis-shapen as the diminishing trace-centered extraction box misses more flux in some regions than in others.

Figure 24 shows the same spectral ratios with each curve divided by its median, to facilitate comparison of the spectral shapes. There is still some tilt or curvature in the spectral ratios when the evolved traces are used. As one would expect from the tightness of the correlation of trace tilt with time (Figure 2), this broad structure is not due to residual error in the tilt of the applied traces. Changes in the spectral ratios are barely perceptible when the STSDAS routine MKTRACE is used to adjust the trace for each exposure. The structure is also not due to minor errors in the determination of the centroid of the spectrum in the spatial dimension during the extraction. A forced shift of 0.1 pixels in the spatial center of a 3 pixel extraction produces a shift of 1.5% in the spectral ratio curve, but does not change its shape or tilt.

Qualitatively, one would expect to find an anti-correlation of narrow-extraction flux with the width of the point spread function (PSF) as "breathing" occurs over the course of an orbit (gradual motion of the secondary mirror relative to the primary mirror) or as other changes affect the focus. The full sample of 39 G430L 52X2 exposures made in the CCD sensitivity monitoring programs was examined to quantify the variations encountered in narrow-box extractions of flux and in the spectroscopic PSF. The ratio of the extraction-box-3 spectrum to the extraction-box-11 spectrum for all 39 exposures is shown in the upper panel of Figure 25. (This panel is similar to the lower right panel of Figure 23, and includes the 6 exposures represented there.) The exposures are color coded from red to violet according to the slope of a linear fit to each curve. The static extraction box correction for 3-pixel extractions is causing differential errors in the flux of up to 15% from the blue end of the spectrum to the red end. The FWHM of a Gaussian fit to each column of the crj image is shown for each exposure in the middle panel of the figure, using the same color coding for each exposure as in the upper panel. Since the Gaussian fits are affected by undersampling, the columns of the crj images were next boxcar smoothed by 3 pixels. The FWHM of the smoothed PSF is shown in the lower panel. This panel most clearly displays the observed sequence of color-dependent PSFs. As expected, at a given column or wavelength, the broadest PSFs correspond to the lowest 3-to-11-pixel flux ratios. An exposure with superior focus in the blue invariably has degraded focus in the red relative to the other exposures, and vice versa.

Figure 26 quantifies the anti-correlation of 3-pixel-extraction flux and PSF width



Figure 25: Top panel: the ratio of spectral extractions of box height 3 to extractions of box height 11 for 39 exposures of a standard star with G430L spanning 7 years. Middle panel: FWHM of Gaussian fits to the columns of the crj images of the star. Lower panel: FWHM of Gaussian fits to the columns of the crj images after they were boxcar smoothed by 3 pixels (see text). The same color is used for an exposure in all 3 panels.

Figure 26: For the exposures used in Figure 25, the normalized extracted flux (x1d(3 pixels)/x1d(11 pixels)) at column 50 divided by that at column 900 versus the boxcar-3-smoothed width of the crj image at column 50 divided by that at column 900.

that can be seen in Figure 25. The quotient of the flux ratio (x1d(3 pixels)/x1d(11 pixels)) in column 50 to column 900 (blue to red) is shown as a function of the quotient of the width of the boxcar-smoothed PSF in column 50 to column 900. (The spectra and width functions were boxcar smoothed by 11 pixels.) For correctly calibrated spectral extractions, the flux ratio (x1d(3 pixels)/x1d(11 pixels)) should be 1 at all wavelengths, so the quotient of any two columns should also be 1. Extractions of 11 pixels or greater give very consistent fluxes, so the error is in the calibration of the 3 pixel extractions. The 3-pixel-extraction blue-to-red flux ratio is in error by less than 5% in 80% of the exposures, but reaches 13% in the worst case.

For every exposure taken with G430L in the sensitivity monitor programs, exposures were taken with G230LB and G750L in the same visit. In all but one case, the exposures in a visit were made within the same orbit. The G430L exposure followed the G230LB exposure by 6 to 11 minutes, and the G750L exposure followed the G430L exposure by 11 to 28 minutes (except for one interval of 73 minutes). The three exposures thus spanned half an orbit to an orbit. The visits were generally spaced at intervals of 2 to 3 months. The differential width of the boxcar-3-smoothed PSF (FWHM(col 50)/FWHM(col 900)) is shown for all three gratings as a function of observing date in Figure 27. The differential widths of the G230LB and G430L PSFs are clearly correlated, and the G750L differential widths somewhat less so. (A halo of scattered light affects the G750L PSF. An asterisk marks the exposure taken in a different orbit.) There Instrument Science Report STIS 2007-03

Figure 27: Differential widths (FWHM), column 50 to column 900, for boxcar-3-smoothed columns of the G430L exposures (green line) shown in Figure 25, and for exposures made with G230LB (blue line) and G750L (red line) in the same orbit (except for the point marked with an asterisk), shown as a function of observing date (MJD).

is no apparent long-term trend in the plots. The changes are not clearly related to either breathing on the time scale of an orbit or to the long-term drift in focus that necessitates the occasional despacing of the primary and secondary mirrors. Focus changes on a variety of time scales are discussed in ISR TEL 2005-03 (Lallo et al., 2005).

Spectral PSFs on the MAMA detectors show greater variation in cross-dispersion width but less color dependence in the variation than the CCD spectral PSFs. Here we examine the sets of exposures used to measure the trace tilt evolution for G140L at the lower position on the detector, G230L, and G430L. The width metric is again the FWMH of a Gaussian fit along the columns of the flt or crj image after boxcar smoothing by 3 pixels, to eliminate measuring errors due to fitting undersampled PSFs. A smoothed width metric (SWM) has been generated by boxcar averaging the width metric over 11 pixels. The SWM at the central column of the detector has a width of:

4.7 pixels with a dispersion of 5.5% for the G140L sample

3.5 pixels with a dispersion of 3.2% for the G230L sample

3.1 pixels with a dispersion of 1.5% for the G430L sample

The blue-to-red width ratio SWM(col. 100)/SWM(col. 900) has an average of:

1.54 with a dispersion of 2.3% for the G140L sample

1.10 with a dispersion of 3.6% for the G230L sample

0.98 with a dispersion of 5.5% for the G430L sample

6. Conclusion

Spectral traces show time evolution (rotation) that has been incorporated into reference files for the most commonly used first order gratings and central wavelengths: G140L(1425), G230L(2376), G230LB(2375), G430L(4300), G750L(7751), G750M(6581), G750M(6768), and G750M(8561). These reference files have been used in the full recalibration of STIS archival data that has been performed as part of the STIS close-out plan. We have delivered post-pipeline software to generate rotated traces for the less commonly used modes. The use of properly rotated traces improves rectified spectral images and spectral extractions made with small extraction boxes, especially for the more recent observations where the traces have deviated most from those that were calibrated early in the operational lifetime of STIS. When the best traces have been used, other factors that limit the accuracy of spectral images and extractions should be considered. Single rows in rectified images must be used carefully, with an understanding of the artifacts due to under-sampling of the point spread function along the slit. Spectral extractions made with small extraction boxes are vulnerable to variations in the size and in the wavelength dependence of the point spread function.

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