

## STIS Echelle Blaze Shift Correction<sup>1</sup>

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**Abstract.** Planned offsets of the STIS Mode Select Mechanism (MSM) result in changes to the nominal calibration curves, particularly noticeable in the echelle modes. The spectral wave calibration exposures (wavevals) obtained with each observation can be used to predict a simple, linear offset of the nominal calibration curve to be used for each MSM shift. In addition, a time dependent variation has been detected which is attributed to small changes in the grating itself. An algorithm has been developed which applies the offsets necessary to correct both the time dependent and MSM shift effects for the echelle modes.

### 1. Introduction

Ultraviolet spectra acquired with the Space Telescope Imaging Spectrograph (STIS) have been periodically shifted in position at the UV MAMA detectors by a small amount to more uniformly age the UV MAMA detectors. This was done by moving the Mode Select Mechanism (MSM) slightly from its nominal orientation for each mode. However, it was observed that these motions caused small errors in the echelle calibration, particularly noticeable in the overlap between orders. Re-calibration for each offset position was possible but time consuming and inefficient. We thought it might instead be possible to correct for this calibration error by using the wavelength calibration spectra acquired with each observation, to indicate the offset, and shift the initially acquired calibration curve accordingly.

### 2. Magnitude and Cause of The Blaze Shift Effect

Figure 1 shows a portion of an echelle stellar spectrum acquired in STIS E230H mode following an MSM shift from the nominal setting. About six adjacent orders of the spectrum near 2575 Å are presented in the figure. The calibration error introduced is approximately linear over each order, causing the slanted appearance. The resulting flux mis-match is about 10% at the overlap regions where the same spectral bandpass is measured simultaneously in adjacent orders.

The calibration error is due to the change in the direction of light incident on the echelle gratings when the MSM orientation is changed. Changing the light incident angle at the echelle, causes two changes in the detected spectrum: the spectrum itself shifts position at the detector, and the grating blaze, or grating efficiency curve, shifts. However these two shifts are by different amounts. This relative shift between the echelle spectrum and the grating blaze function is illustrated in Figure 2. In the upper panel, a spectrum consisting of several orders ( $m$ ,  $m+1$ ,  $m+2$ ) is illustrated with two distinct emission lines (small slit symbols) shown. The grating blaze function is illustrated by the gray, trapezoidal region. Peak grating efficiency is indicated by the bright, central region and the

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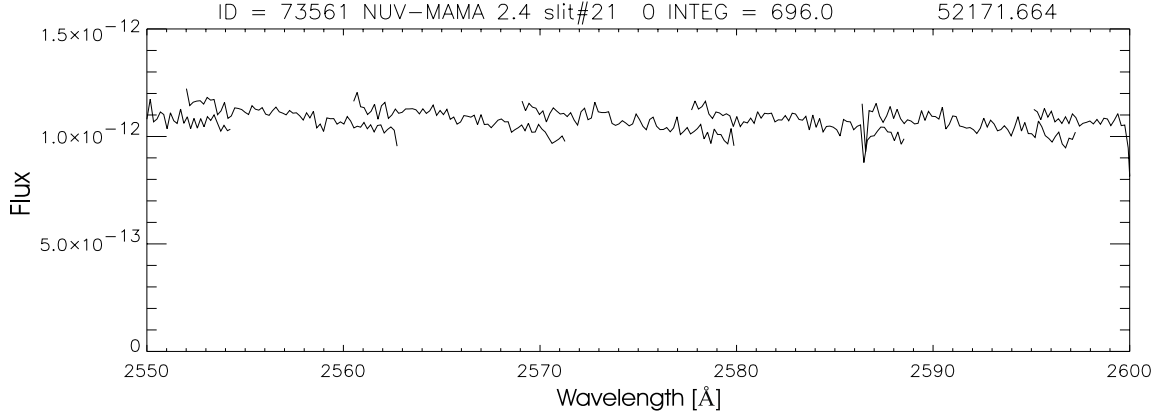


Figure 1. The spectrum of a star near 2575Å with the E230H echelle, following a change of the MSM orientation. Six spectral orders are shown. A systematic calibration error, approximately linear with wavelength over each order has been introduced by the MSM change.

free spectral range by the two diagonal, dashed lines. The lower panel illustrates the changes in this pattern following a change of direction of light incident onto the echelle. The spectrum shifts (indicated by the spectrum offset) and the blaze function shifts (indicated by the blaze function offset), however the magnitude and direction of these two shifts are not equal. The overall result is that the relative position of spectral lines with respect to the blaze efficiency curve has changed. Calibration using a blaze function which does not account for this relative shift between the spectrum and blaze function will result in the error observed.

### 3. Correcting for Echelle Blaze Shift

The blaze function angular shift ( $d\beta_{\text{blz}}$ ) due to a change in the direction of incident light on the echelle ( $d\alpha_{\text{grt}}$ ) in the dispersion direction is

$$d\beta_{\text{blz}} = -d\alpha_{\text{grt}} \quad (1)$$

From the wavecal observations, we can determine the change of the exit angles of light from the echelle gratings in both the dispersion  $d\beta_{\text{grt}}$  and cross dispersion directions  $d\phi'_{\text{grt}}$ . Using the general grating equations (Namioka, 1959), these can be related to the change of dispersion direction input angle  $d\alpha_{\text{grt}}$  as

$$\sin \alpha_{\text{grt}} + \sin \beta_{\text{grt}} = \frac{m\lambda}{\sigma \cos \phi_{\text{grt}}} \quad (2)$$

$$\phi'_{\text{grt}} = -\phi_{\text{grt}} \quad (3)$$

$$d\alpha_{\text{grt}} = -\frac{\cos \beta_{\text{grt}}}{\cos \alpha_{\text{grt}}} d\beta_{\text{grt}} + \left( \frac{\sin \alpha_{\text{grt}} + \sin \beta_{\text{grt}}}{\cos \alpha_{\text{grt}}} \right) \tan \phi_{\text{grt}} d\phi = -d\beta_{\text{blz}} \quad (4)$$

The change of blaze angle is then in general a function of the exit angles in both the dispersion ( $d\beta_{\text{grt}}$ ) and cross dispersion ( $d\phi'_{\text{grt}}$ ) directions for out-of-plane grating mounts, i.e., those for which  $\phi' \neq 0$ . For the STIS echelles the out-of-plane angle is small but not negligible particularly for motion near the cross dispersion direction.

We thus tried to fit the blaze shift ( $\Delta X_{\text{blz}}$ ) with a two parameter function, linear in the dispersion ( $\Delta X_{\text{sp}}$ ) and cross dispersion ( $\Delta Y_{\text{sp}}$ ) directions:

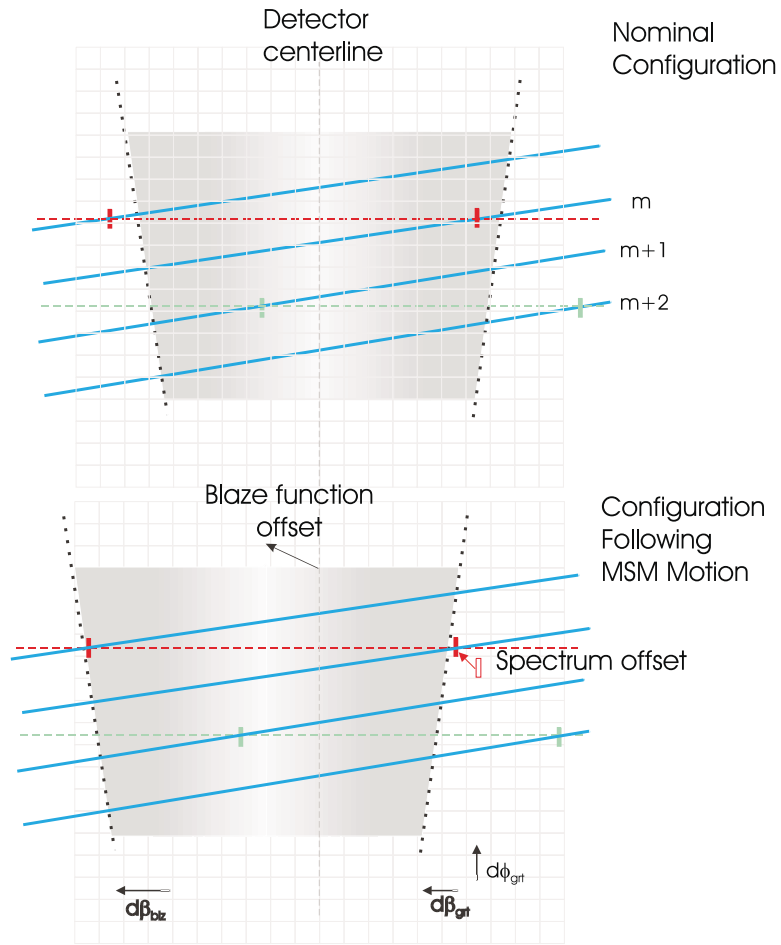


Figure 2. The changes at the detector in spectrum location and grating blaze function due to a change of incident angle on an echelle grating are illustrated. The top panel shows several spectral orders and the position of a few spectral features by the small slit symbols. The grating efficiency curve (blaze) is the gray, trapezoidal region, centered on the detector. After an MSM change, the spectrum and blaze are seen to shift by different amounts, causing the relative efficiency of spectral features to change.

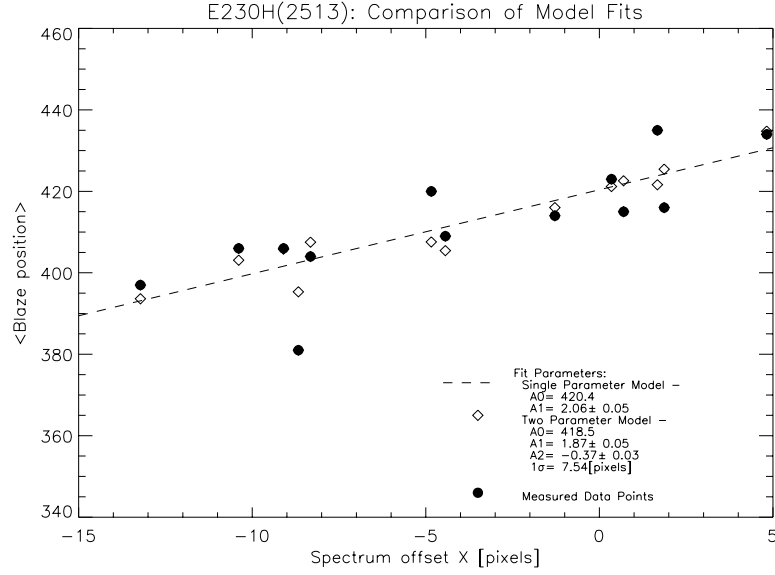


Figure 3. The blaze position as a function of dispersion direction ( $X$ ) spectral offset for a set of stellar observations in mode E230H. The blaze shifts about 60 pixels due to occasional variation of the MSM orientation. The results of estimating the blaze position using only dispersion (single parameter model) or both dispersion and cross dispersion data (two parameter model) are shown.

$$\Delta X_{\text{blz}} = A_1 \Delta X_{\text{sp}} + A_2 \Delta Y_{\text{sp}} \quad (5)$$

A series of observations of mode E230H were selected for an initial test of correlating observed blaze function shift with spectrum shift as determined from the accompanying wavecal spectra. The spectra selected were all stellar with good S/N and few features and were acquired over a period spanning about 1500 days. Relative spectral shifts in dispersion ( $X$ ) and cross dispersion ( $Y$ ) directions were determined for each selected spectrum from the wavecal spectra. Blaze shifts were determined by shifting the echelle ripple pattern (this is the pattern shown in Figure 1) until the overlap regions were coincident.

Figure 3 shows the relative blaze position as a function of the spectrum offset in the dispersion ( $X$ ) direction as the filled circles. The blaze function was seen to shift by about sixty pixels throughout this series of observations. The correlation between blaze and spectral shifts is evident; the dashed line (single parameter model) shows the best, linear fit between these quantities. The separation between the dashed line and the data points indicates the error which would still remain if only this single parameter model were used. The greatest error occurs at the point with the unusually low blaze position of pixel 380, with a residual error of about 20 pixels. Fitting the blaze position as a linear function of the spectral shift in both dispersion ( $X$ ) and cross dispersion ( $Y$ ) yields the results shown in Figure 3 by the unfilled diamond symbols. The improvement compared to the single parameter fit is evident. The distribution of errors is still somewhat large, with a standard deviation of 7.5 pixels.

Examining the details of the remaining errors shows that the largest discrepancies occurred for spectra acquired at substantially different times. Figure 4 shows the difference between the measured blaze position and the two parameter model fit as a function of relative observation time. A correlation which is approximately linear is evident; the measured blaze appears to have shifted about 25 pixels (out of a total in the data of sixty) over the 1500-day period from which these observations were drawn. Including a linear time dependence for the blaze as a third parameter produces the fit shown in Figure 5 (the three parameter model). The improvement compared to

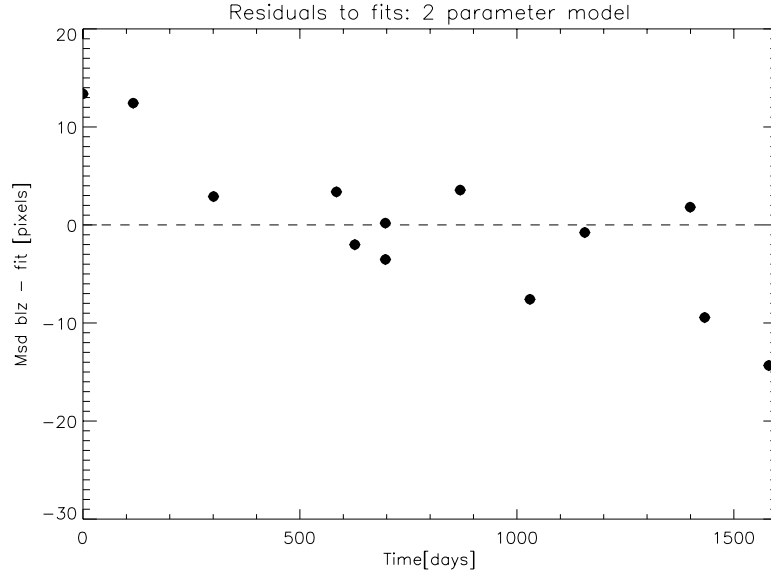


Figure 4. The difference between measured and expected blaze position using the two parameter model (Figure 3) as a function of observation time. The remaining fitting error is clearly correlated with observing time approximately linearly.

the two parameter fit is clear with the standard deviation between measured and fit blaze positions reduced to four pixels. Using such a fit, the blaze position can be well estimated from the spectral shift (both  $X$  and  $Y$ ) and the time of observation. But what is changing with time? We will return to this question in Section 5.

#### 4. Implementation of the Correction Algorithm

To provide the most accurate data for blaze shift correction, all non-proprietary echelle observations of sources with a continuum over the period from launch to December, 2001 were selected. The spectral shifts, in both dispersion and cross dispersion directions, were determined from the accompanying wavecal images. The blaze shift of each spectrum was determined by shifting the echelle ripple pattern until the overlap regions are coincident. Finally a three parameter, linear fit of

Table 1. STIS Echelle Mode Blaze Shift Model Parameters

Mode	A1	A2	A3
E140M	-0.30	0.01	0.008
E140H	-0.66	-0.11	-0.021
E230M	0.10	-0.15	-0.002
E230H	1.49	-0.31	-0.017

blaze position as a function of spectral location ( $X$  and  $Y$ ) and time was produced for each echelle mode. The fit coefficients are presented in Table 1. To apply to a spectrum, the wave calibration image is used to determine the  $X$  and  $Y$  spectral shifts and the observation date provides the time value. The sensitivity curve is shifted accordingly and then applied to the data. This algorithm was implemented in the STIS pipeline reduction package, calstis, version 2.13b.

Figure 6 shows the result of applying this model to the data set of Figure 1 for Mode E230H. The overlap agreement is good to about 1.5%. Similar results are obtained with spectra in all echelle

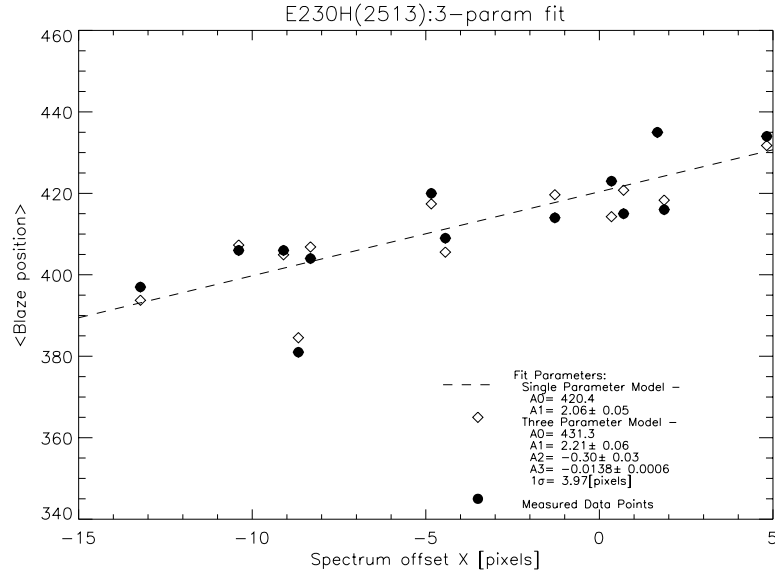


Figure 5. The blaze function measured (filled circles) and fit (open diamonds) using a model linear in dispersion ( $X$ ), cross dispersion ( $Y$ ) and time. Comparison with Figure 3 shows the significant improvement achieved by including observation time in the model.

modes. We conclude that this method, if the time dependent term is included, can produce spectra well corrected for the MSM offsets and time variations observed so far.

The MSM offset procedure for the echelle modes was ended August 5, 2002, so corrections for this effect can be applied to all STIS echelle data accumulated to date. The current incorporation of this algorithm will continue however, to apply a time dependent correction, with the same slope as determined here, to all future observations.

## 5. Time Dependent Variation of Blaze

A variation with time of the alignment of any optical components following the STIS entrance slit or the detector, could cause an apparent shift of the blaze function. But such an instability would also cause a time dependent change in the location of the wavecal spectra. We used a selected set of wavecal spectra to assess the temporal stability within STIS. From a series of echelle observations in Mode E140H acquired over a period of about 1450 days (approximately contemporaneous with the E230H presented in Section 3) we extracted those for which the MSM position repeated, that is the MSM was set to the nominal position for the mode. The spectral locations, as determined by the wavecal spectra, in dispersion ( $X$ ) and cross dispersion ( $Y$ ) are illustrated in Figure 7. Over this four year period, the position of the spectrum varied by no more than  $\pm 2$  pixels in both directions, showing a very high level of internal stability within STIS for the entire optical system following the entrance slit. There may be a very small level of real drift amounting  $\leq 4$  pixels over the four year period in the dispersion and cross dispersion directions but this is negligible when compared with the blaze drift in this same measurement set illustrated in Figure 8. This plot shows the relative measured blaze position over the four year observation period for this same set of data which are nominally at the identical alignment. The blaze position has shifted by over thirty pixels in this time.

The apparent shift of the blaze efficiency function with time could be caused by a change of sensitivity across the detectors, approximately linear in the high dispersion direction. Such a change would not be wavelength dependent but position dependent; it would vary similarly in each order (see Figure 1). Note however, from the results of Table 1, that this time dependent sensitivity

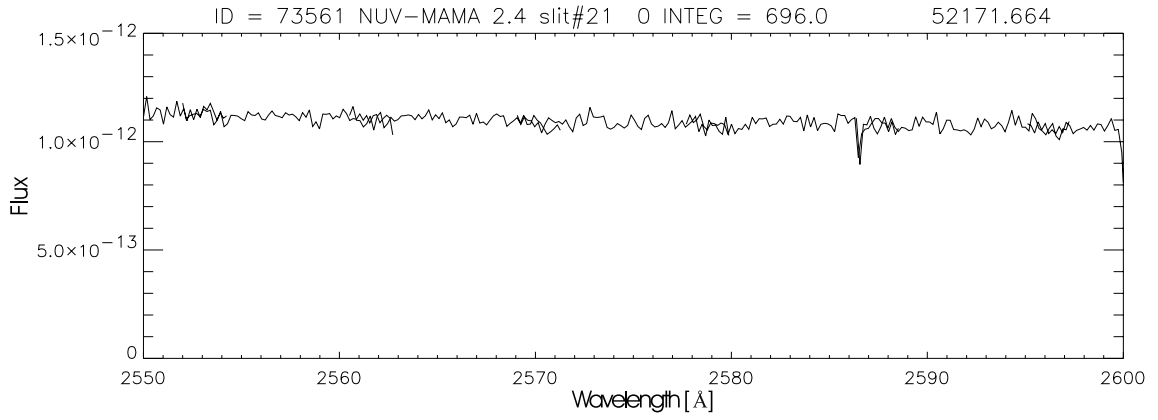


Figure 6. The same spectrum as Figure 1, now corrected using the wavecal spectrum and results from the blaze shift algorithm for Mode E230H.

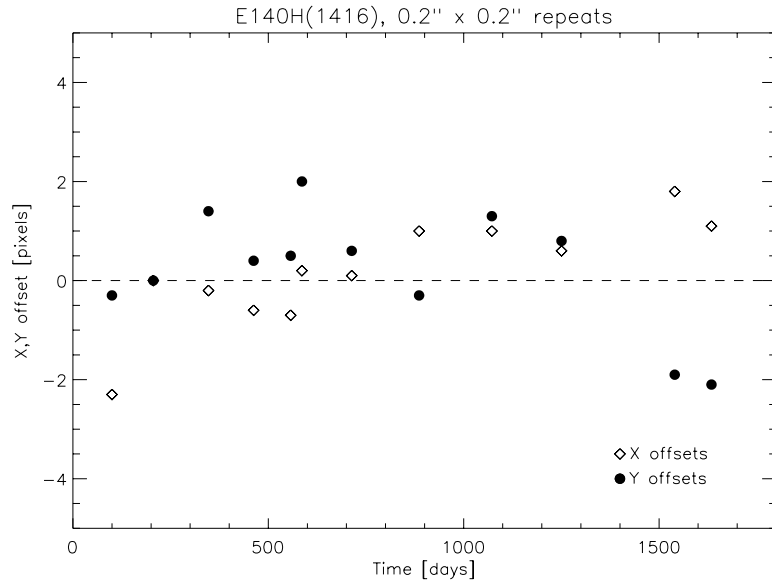


Figure 7. The relative positions of spectra obtained with the E140H echelle over a four year period, with the MSM positioned to the same orientation. The internal temporal stability of this STIS mode is very high; any possible drift is no greater than 4 pixels over this period.

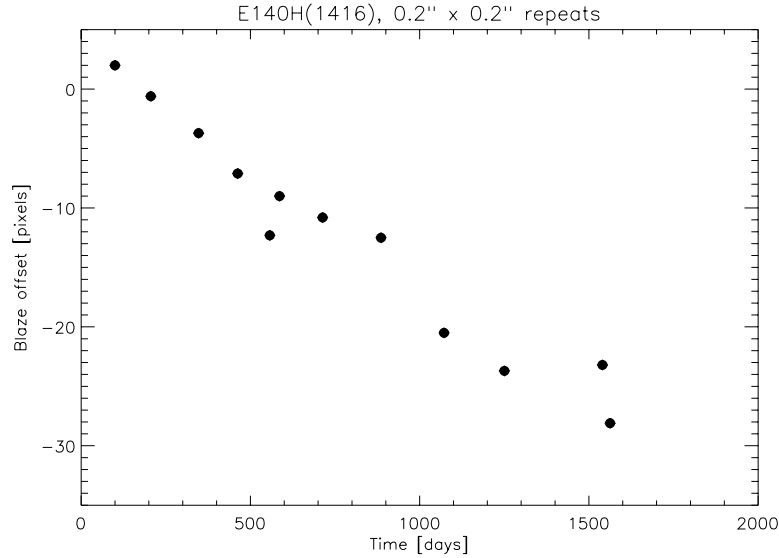


Figure 8. The temporal stability of the blaze function, from the same data set of repeated MSM orientations used in Figure 6. Over this four year period, the blaze function has shifted about 30 pixels while the spectrum shifted no more than 4 pixels in the dispersion direction.

change would have to occur in both MAMA detectors since we see shifts in both detectors. Such a change with time would also show up in all other modes which utilize the MAMA detectors, including mode G230L for example. Any changes in sensitivity in such a first order mode could be due to either a variation with wavelength, the usual interpretation, or position on the detector. The dispersion direction for G230L is the same as the high dispersion direction for echelle mode E230H. Repeated sensitivity calibrations of mode G230L with wavelength are presented in Figure 9 of *Instrument Science Report STIS 99-07* over the time period 1997.38–2000.38. The variation with wavelength is not linear and is no more than +2% to –1% at any wavelength over this time period. This data suggests that this detector is highly stable both positionally and with wavelength. From these results we would expect to see echelle spectra taken over this period to have order overlap errors no larger than these limits, provided the MSM was in the same position. Figure 9 shows five orders from E230H of a calibration white dwarf taken at 1998.4 (upper curve) and 2001.9 (lower curve). The slit and MSM position was identical for both observations and the spectral locations were within 3.6 pixels (cross dispersion) and 0.5 pixels (dispersion direction). Both spectra have been approximately normalized and the earlier spectrum has been offset for clarity. The calibration and order overlap is very good for the initial spectrum but 3.5 years later the systematic calibration error is about 8%, not consistent with the measured sensitivity stability. The blaze shift effect does not seem to be due to any change in detector sensitivity.

For the shorter wavelength detector, similar stability tests with Mode E140L (Figure 8, Bohlin) do show some variability with time. The variation with wavelength is not monotonic; interpreting this as a possible positional sensitivity error would require more detailed modeling to understand the effect on the echelle blaze curve. However the variation shown is likely to be due to low level contamination and thus be a true wavelength dependent effect and not a positional sensitivity variation at all. The mirror coatings for STIS modes in this wavelength range were tailored to have the least sensitivity to contaminants near 1216 Å and should be most sensitive near 1600Å. Mode G140L has decreased least near 1300 Å and most near 1600 Å similar to expectations.

Without other possibilities, it appears that the echelle blaze itself must be changing in time, that is the grating groove angle is slowly changing. The rate of blaze shift for each mode is listed in Table 2; it is very small, measured in either pixels or in tilt of the grating grooves (arcseconds/year).

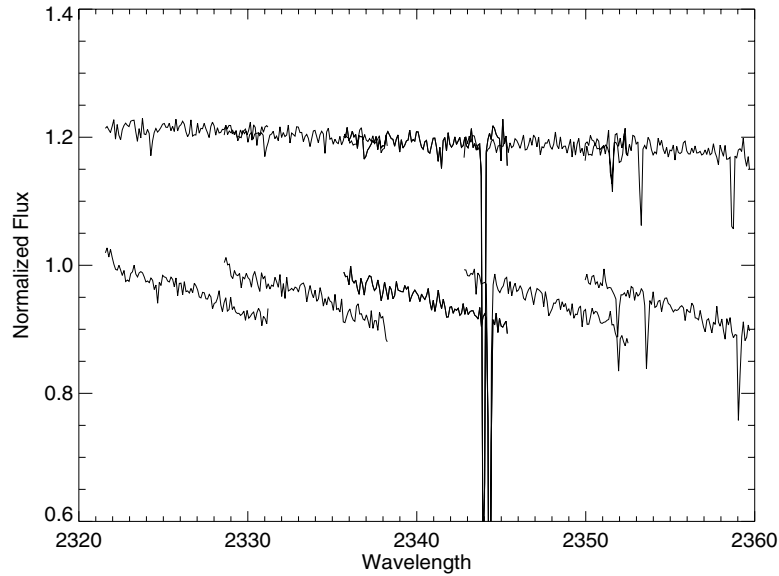


Figure 9. A portion of normalized, E230H spectra of a white dwarf calibration star from 1998.4 (upper, offset for clarity) and 2001.9 (lower) taken with the same slit and same nominal MSM positions. The initial, consistent calibration is in error by about 8% after 3.5 years, though the detector sensitivity has varied by no more than 2%.

The indicated rate of change of Mode E230M is within the measurement errors, but the rates for the other three modes appear real. Without the high degree of stability of *HST* and STIS such small changes would be difficult to detect. All four echelles are replicated from master rulings. One possible mechanism for blaze change is very slight shrinkage with time of the epoxy used in replication, though we note that the measured rates of change are not well correlated with groove depth as might be expected in a simple model.

Table 2. STIS Echelle Mode Blaze Shift Rate

Mode	Blz shift [pixels/yr]	Blaze tilt change ["/yr]
E140M	2.9	5.9
E140H	7.7	15.4
E230M	0.7	1.5
E230H	6.2	12.5

## 6. Summary and Recommendations

The calibration error introduced by shifting the MSM from its nominal orientation can be well corrected by using the original sensitivity curve for each echelle mode, shifted according to the spectral shifts determined from the associated wavecal spectra and using a linear, time dependent term. Linear fits to data collected over a 4-year period provide the necessary coefficients for the algorithm, presently incorporated in the pipeline reduction procedure, *calstis*. Shifting the MSM for the echelle modes has been halted as unnecessary so that application of the shift terms is now incorporated only for archival data. However the time dependent term will be continue to be applied for future reductions. As such, the time dependence of the blaze function should continue to be

monitored for any changes from the simple, linear dependence used in the current model. The cause of this time dependent term appears to be a change in the gratings themselves.

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