

Calstis7: Two-dimensional rectification of spectroscopic data in the STIS Calibration Pipeline

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ABSTRACT

This report describes the two-dimensional rectification of STIS spectroscopic data performed by calstis7 in the STIS calibration pipeline. Two-dimensional rectification produces a flux-calibrated, rectified image with distance along the slit running linearly along the y axis and dispersion running linearly along the x axis.

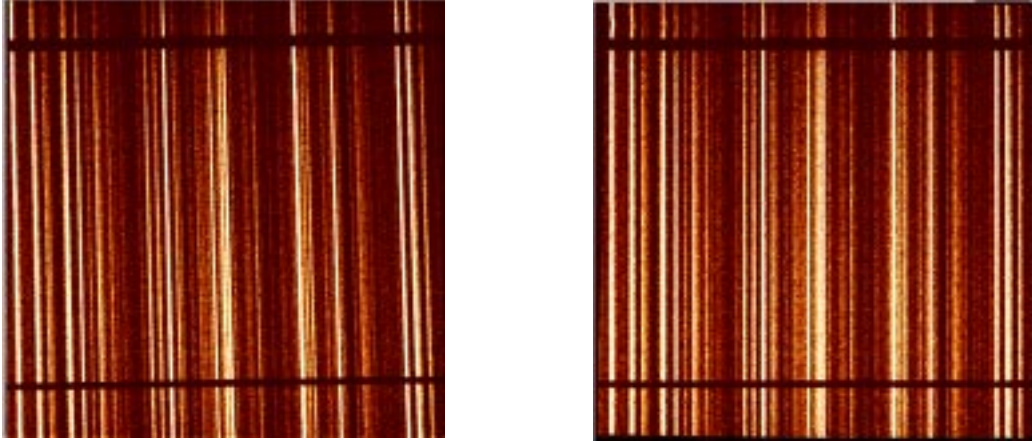
1. Introduction

Calstis7 (and its corresponding IRAF task **x2d**) performs two-dimensional (2-d) rectification of STIS spectroscopic images following basic 2-d image reduction (performed by *calstis1/basic2d*; see ISR 95-007 for more details about *calstis1*, and ISR 98-14 for more details about **basic2d**). From an input flat-fielded (and if appropriate cosmic-ray-rejected) image (`_flt` or `_crj` file) an output image (`_x2d` or `_sx2` file) is produced that has dispersion running linearly along the x-axis and distance along the slit running linearly along the y-axis. One rectified image is produced for each spectral order. This processing is represented schematically in Figure 1, where both unrectified (input) and rectified (output) images are shown for a long-slit, line lamp observation. 2-d rectification is not done for imaging observations or echelle spectroscopic observations in the pipeline, although these can be done off line using the **x2d** task in STSDAS. 2-d rectification is also performed as part of standard wavecal processing (see ISR 98-12 for more details about wavecal processing). Execution of 2-d rectification is controlled by the X2DCORR calibration switch in the primary header of the input file. After 2-d rectification, customized spectral extractions can be performed on the rectified image if desired.

The report is organized as follows:

- Section 2 describes the coordinate systems, notation, definitions, and sources of information required for the 2-d processing;
- Section 3 describes the detailed processing steps for the rectification.

Figure 1: Example of 2-d rectification for a long-slit line lamp observation.



2. Definitions, notation, and sources of information for 2-d processing

The overall flow diagram for *calstis7* processing is shown in Figure 2. Whether 2-d rectification is performed is determined by the setting of the X2DCORR calibration switch in the primary header of the input data file. In the pipeline, this switch is set to PERFORM for all supported (CFSTATUS keyword set to SUPPORTED), non-echelle *spectroscopic* data. The input file in the pipeline is the output of basic 2-d imaging processing, which is either a flat-fielded image (*rootname_flat.fits*) or if it exists, a cosmic-ray rejected image (*rootname_crj.fits*). Although it is not done in the pipeline, 2-d rectification can be performed on a raw input image (*rootname_raw.fits*) off line using the **x2d** IRAF task. 2-d rectification is not performed in the pipeline for either imaging or echelle data, although again, it is possible to do this using the off line **x2d** task.

Two stages of the 2-d rectification are also controlled by the primary header calibration switch settings: FLUXCORR and HELCORR. If either of these switches is set to OMIT, that step of 2-d rectification is not performed. In the pipeline, these switches are set to PERFORM in the same way as the X2DCORR switch. While there is a calibration switch for DISPCORR, it is ignored by *calstis7*, i.e., no matter what the setting of this switch in the primary header of the input file, application of the dispersion solution will still be made, since this is fundamental to 2-d rectification. If the switch is inadvertently set to OMIT, DISPCORR will still be performed, and the switch setting is changed to COMPLETE in the output file header. Note also that the correction for small-scale geometric

distortion is not currently implemented, and this switch is also ignored since this step is not currently performed. The calibration reference files used in *calstis7* are shown in Figure 2, and are described in detail in an interface control document, ICD-47, which is available via the STIS WWW page under the link for Calibration, and then Reference File History.

The processing for 2-d rectification is done by looping over pixels in the *output* image, whose size and reference pixel coordinate system are defined by the so-called World Coordinate System parameters in the Spectrum Distortion Correction calibration reference table (SDCTAB) for each unique combination of grating, spectral order, and central wavelength. The SDCTAB actually contains coordinate information rather than distortion information; the name reflects its connection with the imaging distortion table (IDCTAB). The world coordinate system parameters in the SDCTAB have the following definitions:

NPIX1, NPIX2:	size of the output image in reference pixels
CRPIX1, CRPIX2:	the reference pixel in the output (rectified) image
CRVAL1, CRVAL2:	coordinate values (wavelength and distance along the slit) at CRPIX _i ; note that CRVAL2 is <i>defined</i> to be zero, i.e., the center of the image in Y is the nominal position defined for the center of the slit.
CDEL1:	Angstroms per pixel in output image
CDEL2:	arcseconds per pixel (along slit) in output image

Some of these parameters are modified depending on whether binning or subarrays are used in the input image. In 2-d rectification, approximately 80 pixels are added to NPIX_i beyond the nominal values to account for possible shifts such as those associated with the MSM positioning uncertainty, and heliocentric velocity shifts. The values of CD1_1 and CD2_2 in the output image are filled with the CDEL1 and CDEL2 values from the SDCTAB reference file table.

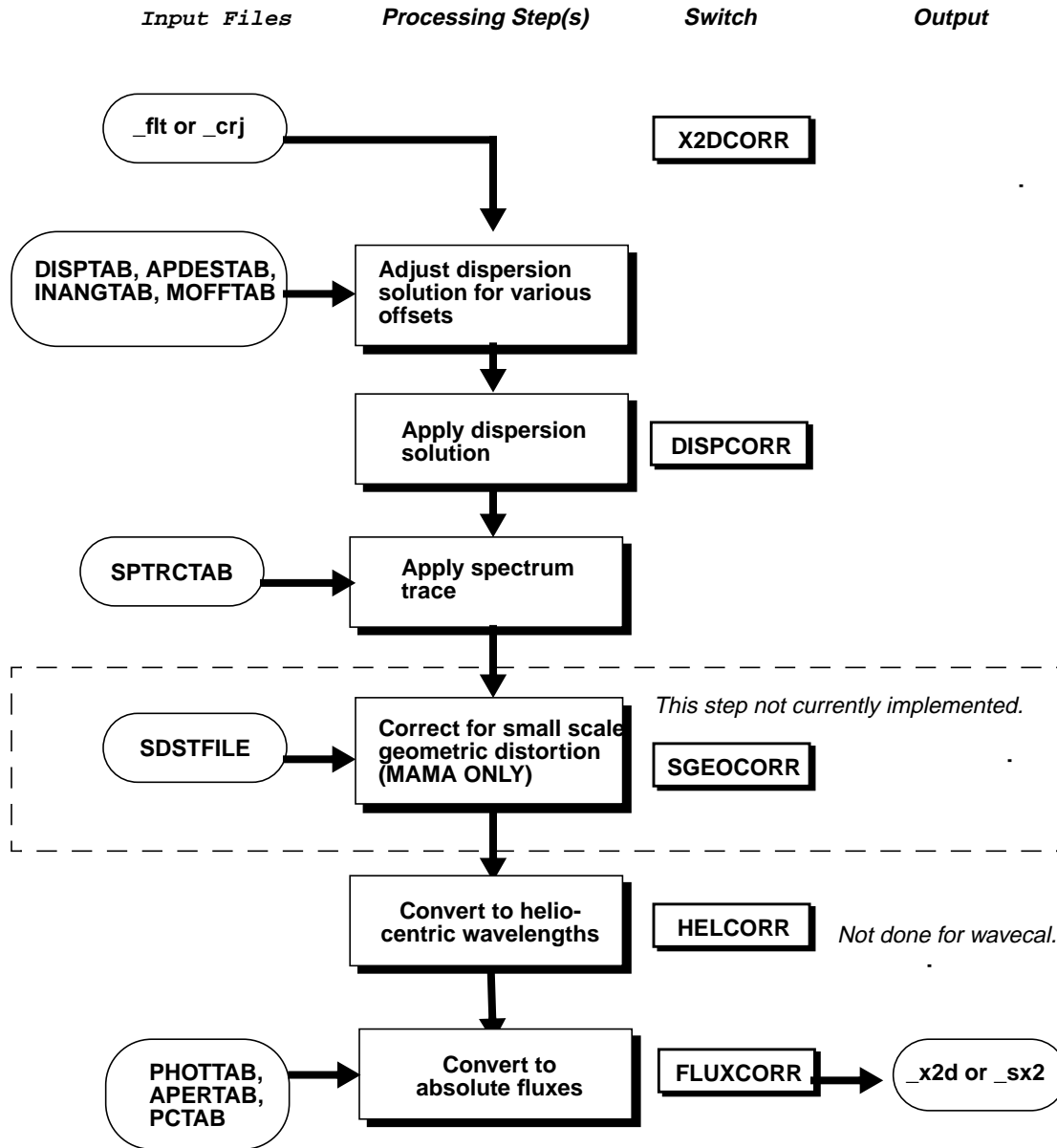
The reference pixel coordinate system is unbinned detector pixels without the over-scan regions for the CCD and native format (1024x1024) detector pixels for the MAMAs. Correspondingly, all information in the calibration reference files and tables used in *calstis7* is also in reference coordinates. The LTV_i and LTM_{i_j} keywords give a linear mapping from the reference pixel coordinate system to the pixel coordinate system of a particular image as follows:

$$\begin{aligned} X &= X_{\text{ref}} \times \text{LTM1_1} + \text{LTV1} \\ Y &= Y_{\text{ref}} \times \text{LTM2_2} + \text{LTV2} \end{aligned} \quad \text{Equation (1)}$$

LTM_{i_j} is the reference pixel size in units of the current pixel size, and LTV_i is the location, in the current coordinate system, of pixel zero of the reference coordinate system. Note that in IRAF indexing, the first pixel is number one, and the pixel number is an integer at the center of the pixel so, e.g., the first pixel runs from 0.5 to 1.5. For more details

about the reference pixel coordinate system, including the values of the LTVi and LTMi_j keywords for various types of CCD and MAMA images, see STIS ISR 98-10.

Figure 2: Flow diagram for *calstis7* as run in the STIS calibration pipeline.



We use the following additional notation for the input and output coordinate systems throughout the ISR, and illustrate the coordinate systems used in Figure 3:

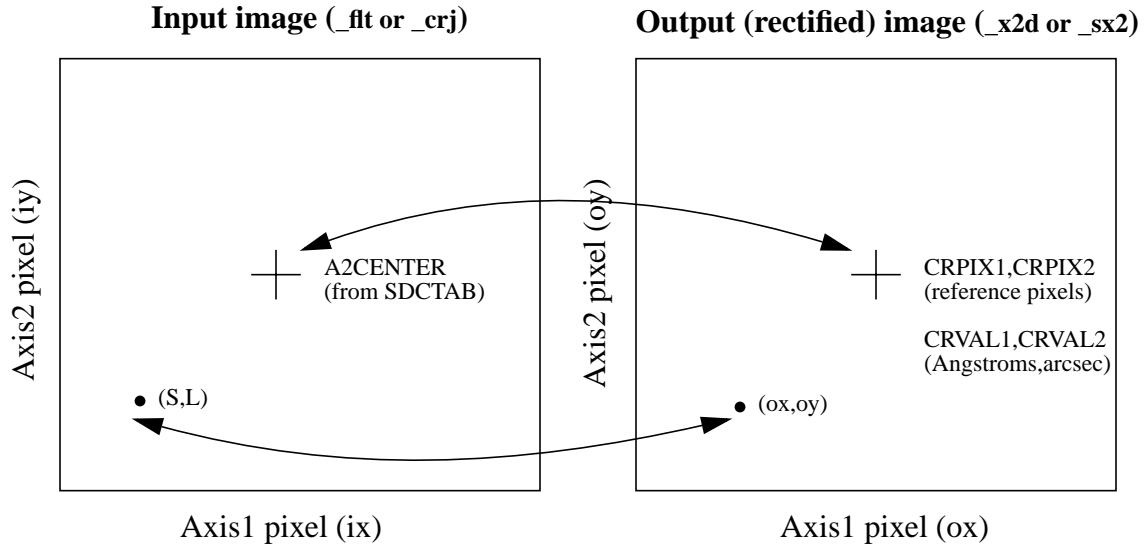
ox, oy

pixel coordinates in the output image

S, L	the point in the input image corresponding to (ox, oy), <i>in reference coordinates</i> (S and L stand for “sample” & “line”)
ix, iy	pixel coordinates in the input image corresponding to (S,L)
A2CENTER:	detector line number at which (or with respect to which) reference data were measured, in particular the dispersion relation or the spectrum trace

Coordinates in the input image may differ from (S,L) for several reasons: because the input image may be a subarray, binned, or in MAMA high-res pixels (2048x2048). The LTV and LTM keywords give the mapping from (S,L) to pixels in the input image. For each imset within an input image, and each spectral order within an imset, a loop over pixels in the rectified (output) image is performed; for each pixel in the output image the corresponding point in the input image is located, and an interpolation performed at that point to get the data value for the output pixel.

Figure 3:



In the mapping between output and input pixels, several known offsets of the spectrum from its nominal location are accounted for, and several other parameters such as the dispersion relation coefficients and incident angle corrections that need to be applied to the data are read from various calibration reference tables. These offsets and corrections are not shown in the figure. The following additional notation, definitions and sources of information required by *calstis7* are summarized in Table 1.

Table 1. Definitions and sources of information for *calstis7* processing in the pipeline.

Parameter	Source	Explanation
NPIX1, NPIX2, CRPIX1, CRPIX2, CRVAL1, CRVAL2, CDEL1, CDEL2, A2CENTER	SDCTAB	Size and reference coordinate system for the output image. For more details, see section 2
m NCOEFF COEFF[i]	DISPTAB	m = spectral order NCOEFF = number of dispersion solution coefficients coefficients of dispersion solution (see Equation 2)
A2DISPL	SPTRCTAB	Y-offset of the spectrum trace from A2CENTER
IAC_coeff1, IAC_coeff2	INANGTAB	two arrays of incidence angle correction coefficients
delta	APDESTAB	the offset (arcsec) in the dispersion direction from the slit used to determine the dispersion relation to the current slit, where the OFFSET1s are from the APDESTAB: delta = OFFSET1(current slit) - OFFSET1(dispersion slit)
MOFFSET1, MOFFSET2	primary header key- words in the input file	deliberate offset ("dither") for the MAMA detectors to pre- vent targets from always falling at the same location on the detector
MAMA_coeff1, MAMA_coeff2	MOFFTAB	two arrays of MAMA offset correction coefficients
ASN_MTYPE	extension header key- word in the input file	Used to evaluate whether the observation being processed is a wavecal.
SHIFTA1, SHIFTA2	primary header key- words in the input file	uncertainty in MSM position, measured by cs4 from wave- cal observations
T_{λ}^{sys}	PHOTAB	System throughput.
T^{ap}	APERTAB	Aperture throughput for a point source
H	PCTAB	H is the correction for an infinite extraction box height divided by the default extraction box height averaged over wavelength

3. Detailed description of 2-d spectral processing

The detailed processing for 2-d rectification involves loops over several hierarchical levels in the output image. These loops are performed in the following order:

- Loop over imsets in the input data file;
- Loop over each spectral order within an imset;
- Loop over each line (oy) of the output image;
- Loop over each sample (ox) of the output image line.

We describe the processing in each loop (and the processing done outside the loops) in detail below. The information read from the reference file tables is detailed in Table 1.

Outside the loops over imsets and spectral orders:

- *Read required information from the APDESTAB, APERTAB and SDCTAB reference file tables.*

For the SDCTAB, all rows that match the optical element (i.e. grating) and central wavelength, that is, all spectral orders (just one for long slit, but many for echelle) are read into memory. The range of spectral orders is used to set the limits on the loop over spectral orders. A2CENTER from the SDCTAB is the line number on the detector corresponding to CRPIX2 of the output image (see Figure 1).

Within the loop over imsets:

- *Compute the heliocentric correction factor.*

The correction of wavelengths to a heliocentric reference frame is controlled by the calibration switch HELCORR — if this switch is set to PERFORM then the correction is made. The functional form of the correction (shown below) requires the calculation of the heliocentric velocity (v) of the earth in the line of sight to the target.

$$\lambda_{helio} = \lambda_{obs} \left(1 + \frac{v}{c} \right)$$

where

λ_{helio} is the heliocentric wavelength,

λ_{obs} is the observed wavelength,

v is the component of the earth's velocity in the direction of the target,

c is the speed of light.

The derivatives of low-precision formulae for the Sun's coordinates described in the *Astronomical Almanac* are used to compute the earth's velocity vector at the time of the epoch of the observation; the target coordinates are also precessed to the epoch of the observation, and a dot product between the velocity vector and the unit target position vector is computed to determine the earth's velocity in the line of sight to the target. The algorithm does not include Earth-Moon motion, Sun-bary-center motion, nor light time correction from the Earth to the Sun. This value for the earth's velocity should be accurate to ~0.025 km/sec during the lifetime of STIS. (Note: the uncertainty of 0.025 km/s is much less than the ~2.6 km/s resolution obtained with the STIS high dispersion echelle gratings.)

Within the loop over spectral orders:

- *Read the in-memory list of parameters from the SDCTAB.*

Information for the order being processed is extracted from the in-memory list read earlier from the SDCTAB table (see Table 1). The size for the output image and the coordinate parameters CRPIXi and CDELTi are then scaled depending on the binning of the input image, as specified by LTM1_1 and LTM2_2 for the input image (see Equation (1)).

- *Read the dispersion coefficients (DISPTAB), spectrum trace (SPTRCTAB), and incidence angle correction (INANGTAB) reference file tables.*

The entries in the DISPTAB and SPTRCTAB tables are indexed by A2CENTER. For these two tables, the set of rows corresponding to the current spectral order, optical element and central wavelength is read. For echelle observations, there may be just one matching row, but for first order there should be many rows, each for a different location A2CENTER on the detector in the cross-dispersion direction. For the INANGTAB, there will generally be only one row that matches the current grating, central wavelength, and spectral order.

- *If the detector is a MAMA, read the MAMA offset correction reference file table (MOFFTAB).*
- *If the observation is not a wavecal, read the SHIFTA1,2 keywords from the SCI extension header*

The ASN_MTYPE is checked to determine whether the observation being processed is a wavecal. If the observation is not a wavecal, the SHIFTA1, SHIFTA2 keywords are read from the SCI extension header. These offsets are calculated by the wavecal processing (see ISR 98-12 for more details about wavecal processing) and have been converted by *calstis4* to reference pixel size.

- *Read the aperture description table (APDESTAB)*

Read the aperture description table to get the offset of the slit from the slit used to determine the dispersion relation [OFFSET1(dispersion slit) in Table 1 definition of delta]. This table was read earlier to get the offset from the position reference slit [OFFSET1(current slit) in Table 1 definition of delta].

- *Process each line (oy) of the output image.*

For each line (oy) of the output rectified image the corresponding line (L) in the input image is located. A first approximation L0 to L is determined by converting to the appropriate reference pixel coordinates (first term in equation below) and accounting for the nominal spectrum location (A2CENTER from SDCTAB) and known offsets:

$$L0 = [(oy - CRPIX2) / LTM2_2] + A2CENTER + MOFFSET2 + SHIFTA2$$

CRPIX2 and A2CENTER are from the SDCTAB, but LTM2_2 is from the input file extension header. L0 is in reference coordinates because it must be compared with

the A2CENTER columns in the DISPTAB and SPTRCTAB. Using the values of A2CENTER from the DISPTAB and SPTRCTAB tables, the rows for which the values of A2CENTER bracket L0 are determined. Linear interpolation is then used on the parameters in those two rows to get their values at L0. If L0 is smaller than the smallest A2CENTER or larger than the largest A2CENTER, the table values are not extrapolated; the values in the row with A2CENTER closest to L0 are used.

The relationship between detector axis1 position (S) and wavelength is specified by the dispersion solution (Eqn 2):

$$S = COEFF[1] + COEFF[2] \times m \times \lambda + COEFF[3] \times m^2 \times \lambda^2 + COEFF[4] \times m + COEFF[5] \times \lambda + COEFF[6] \times m^2 \times \lambda + COEFF[7] \times m \times \lambda^2$$

where COEFF[i] are the elements of an array of dispersion coefficients from the DISPTAB, NCOEFF is the number of coefficients (also from the DISPTAB), and m is the spectral order.

The dispersion coefficients from the DISPTAB are adjusted for the incident angle correction:

$$COEFF[i] = COEFF[i] + IAC_coeff1[i] * \delta$$

$$COEFF[1] = COEFF[1] + IAC_coeff2[1] * \delta + IAC_coeff2[2] * \delta^2$$

If the observation uses a MAMA detector, an additional MAMA offset correction is made to the dispersion coefficients:

$$COEFF[i] = COEFF[i] + MAMA_coeff1[i] * MOFFSET1 + MAMA_coeff2[i] * MOFFSET2$$

If the observations is not a wavecal, add the pixel shift found from the wavecal to coeff[1]:

$$COEFF[1] = COEFF[1] + SHIFTA1$$

- *Process each sample (ox) in the current line of the output image.*
 - Compute the heliocentric wavelength from ox and divided by the heliocentric Doppler correction factor (see above) to get the observed wavelength:

$$\lambda_{helio} = (ox - CRPIX1) * CDELTA1 + CRVAL1$$

$$\lambda_o = \lambda_{helio} / (1 + v/c)$$

- Apply the dispersion solution at the observed wavelength (Equation 2) using the modified dispersion coefficients to get S.

- Evaluate the spectrum trace function at S to get A2DISPL, and add to L0 to get L (note that S and L are still in reference pixels)

$$L = L0 + A2DISPL$$

- *not currently implemented*: Add small-scale geometric correction to (S,L).
- Apply LTV & LTM to convert (S,L) from reference coordinates to actual image coordinates (ix,iy); see Equation (1).
- Bilinear interpolation in the input image at (ix,iy) is used to get the data value to assign to the output at (ox,oy). The output pixel value is a weighted sum of the values of the four pixels nearest (ix,iy) in the input image. The weights depend on the distances in X and Y from (ix,iy) to each of the four pixels, and the sum of the weights is normalized to one. The output science value is:

$$\text{outsci}[\text{ox},\text{oy}] = w1 \times \text{sci1} + w2 \times \text{sci2} + w3 \times \text{sci3} + w4 \times \text{sci4}$$

where w1 through w4 are the weights, and sci1 through sci4 are the input science values at the four nearest pixels to (ix,iy). The errors are interpolated using the same weights as for the science data, except that the errors are combined in quadrature. The error array value at (ox,oy) is:

$$\text{outerr}[\text{ox},\text{oy}] = \sqrt{w1 \times \text{err1}^2 + w2 \times \text{err2}^2 + w3 \times \text{err3}^2 + w4 \times \text{err4}^2}$$

where err1 through err4 are the error array values at the four pixels.

- *not currently implemented*: Determine the factor (Jacobian) by which to multiply the interpolated value to conserve flux. This is not done because the flat field reference images have been made with the assumption that the input image would be sampled rather than integrated when interpolating.
- Convert to absolute flux.

The output SCI and ERR data are corrected (in-place) for telescope throughput and detector sensitivity. The data before correction are in counts; after correction the BUNIT keyword in the science and error extension headers is set to “erg /s /cm**2 / angstrom /arcsec**2”.

Counts are converted to specific intensity by multiplying by:

$$\frac{h \times c \times G}{t \times T_{\lambda}^{\text{sys}} \times \lambda \times A_{\text{HST}} \times d \times m_s \times W}$$

where:

h = Planck's constant (erg-sec)

c = speed of light (cm/sec)

G = analog to digital gain (electrons/DN); only applies to CCD, =1 for MAMA

t = exposure time (sec); from extension header keyword EXPTIME

λ = wavelength (cm) in the output image (see above for how this determined)

T_{λ}^{sys} = system throughput for infinite extraction box height, from the PHOTTAB

A_{HST} = area of the HST primary mirror (45238.93416 cm²)

d = dispersion (angstroms/pixel) = CDELTA1 (see Table 1)

m_s = image scale along slit (arcsec/pixel) = CDELTA2 (see Table 1)

W = slit width (arcsec), from the APDESTAB

The resulting fluxes are for a diffuse, continuum source. Four keywords are written to the output SCI extension headers to aid in the interpretation of the fluxes for other cases. DIFF2PT is for converting to flux for a point source and is discussed further below. CONT2EML is a factor for converting to flux for a diffuse, emission line source. SCALE_A1 is the scale of the output image in arcsec/pixel in the dispersion direction. OMEGAPIX is the solid angle of a pixel in square arcseconds. These keywords are all described in the HST Data Handbook, 1997, volume 1, chapter 23.

DIFF2PT can be used in the following way to extract a 1-d spectrum of a point source from the 2-d flux calibrated image. For each pixel in the first axis, sum the SCI image values over 11 pixels (seven for MAMA echelle) centered on the target spectrum, and multiply the sum by DIFF2PT. The number of pixels (seven or 11) over which to sum is the default extraction box height, as given in the XTRACTAB. The DIFF2PT keyword is assigned the value ($m_s \times W \times H$) / T^{ap} , where T^{ap} is the aperture throughput for a point source taken from the APERTAB, and H is a correction factor taken from the PCTAB. H is the throughput for an infinite extraction box height divided by the throughput for the default extraction box height. Since H and T^{ap} are functions of wavelength and only one value is written to the header, they are averaged over the wavelength range of the grating.

For first order modes, the plate scale in the dispersion direction is a weak function of wavelength. This will be discussed in a future instrument science report by Bowers et al.

4. Future Enhancements

Spectroscopy with the cross disperser gratings is not supported. Aside from the fact that reference tables have not been generated to describe the dispersion and distortion, *calstis6* and *calstis7* only handle the case of dispersion in the first axis direction. We intend to modify *calstis6* and *calstis7* so that, for cross dispersed data, these routines will first transpose the input image, and then continue processing as for the normal gratings. This change will also affect wavecal processing, in that *calstis12* will need to swap SHIFTA1 and SHIFTA2 when copying the shifts from the 2-d rectified wavecal header to the science file header.

In the future it may be decided to implement flux conservation when interpolating. This would be a significant change in calibration and would have to be coordinated with changes in the flat fields. This is because the geometric correction resulting from applying the dispersion solution and 1-d trace changes the pixel area by different amounts in different parts of the image. For the case of uniform input illumination, for example, when the optical distortion compresses the light into a smaller area in one region of the detector than in another, the count rate per pixel will be higher in the first region. This difference can be taken out either by the flat field or by a flux conserving correction for distortion, but not both. Currently this is done with the flat field, and the interpolation does not conserve flux. Changing to a flux conserving interpolation would therefore require new flat fields.