

Calstis6: Extraction of 1-D Spectra in the STIS Calibration Pipeline

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ABSTRACT

This report updates and extends the discussion of STIS ISR 97-02 on the extraction of 1-D spectra performed by calstis6 in the STIS calibration pipeline. Calstis6 processes flat-fielded, 2-D science images to produce one-dimensional spectra using an unweighted extraction algorithm. The resultant flux- and wavelength-calibrated spectra are stored in 3-D binary tables.

1. Introduction

This ISR discusses the extraction of one-dimensional (1-D) spectra in the STIS calibration pipeline, which is performed by *calstis6* following basic 2-D processing (*calstis1*). It updates and extends the information presented in STIS ISR 97-02 by Hulbert et al. in February 1997, and describes *calstis6* as of version 2.0 of the **calstis** calibration software.¹ The most significant changes since that time are pipeline extraction of 1-D spectra for first-order gratings (extraction was initially performed only for echelle observations), the use of a global offset (if needed) for echelle extraction, and the addition of new information to the output file detailing the location of the extracted spectra.

The report is organized as follows:

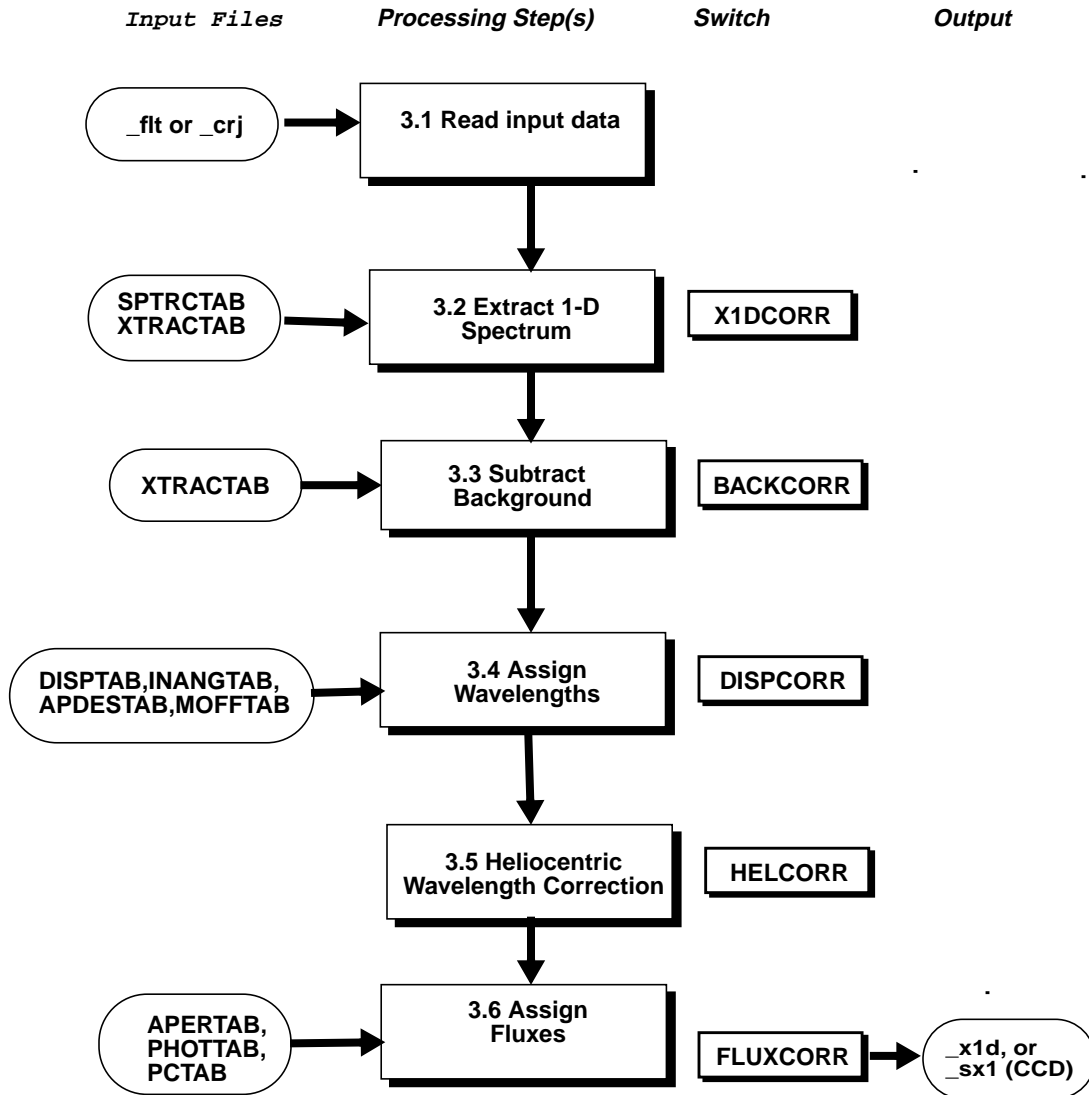
- Section 2 provides an overview of the processing flow, including the calibration switch settings and the references files required at each step in the flow.
- Section 3 gives detailed information on the *calstis6* processing steps.
- Section 4 describes the data quality and error propagation performed by *calstis6*.
- Section 5 summarizes the output data format.
- Section 6 provides detailed information on the calibration reference files used by *calstis6*.

1. The version of **calstis** used to calibrate data can be found in the primary header keyword CAL_VER.

2. Overview

Calstis6 is the module within the **calstis** pipeline calibration software that performs the extraction of one-dimensional spectra from an input flat-fielded (**_flt.fits*) or cosmic-ray-rejected (**_crj.fits*) 2-D image, which is the output of basic 2-D processing (*calstis1*; see STIS ISR 98-26, Hodge et al. 1998). An overview of the steps in the *calstis6* processing flow are shown in Figure 1. As with all **calstis** processing, the 1-D processing is controlled by the calibration switch settings, and requires specific calibration reference files for each step. The calibration switches and reference files that control the *calstis6* processing are shown in Figure 1. All of these switches must be set to **PERFORM** for the proper operation of *calstis6* in the pipeline. Upon completion of a calibration step,

Figure 1: *Calstis6* Processing Flow.



the switch setting is changed to COMPLETE in the output data file header.

It was originally envisioned that a small scale distortion correction processing step would be performed for MAMA data using the calibration switch SGEOCORR and the calibration reference file SDSTFILE (*_ssd.fits). However, this processing step was found to be unnecessary, and there are no plans to implement it in the future. The SGEOCORR switch is therefore always set to OMIT, and the SDSTFILE keyword is (for MAMA data) always filled with 'N/A' (not applicable) in the input and output data files.

There are numerous types of data for which 1-D extraction is not performed in the pipeline, including imaging and slitless spectroscopic observations. All types of data not processed through *calstis6* in the pipeline are identified in Table 1. That is, if any of the conditions identified in Table 1 are true, 1-D extraction is *not* performed.

Table 1. Data types *not* processed through *calstis6* in the STIS pipeline.

Keyword		value
SCLAMP	!=	NONE
OBSTYPE	=	IMAGING
OPT_ELEM	=	PRISM
APERTURE	=	F25* 50* F28* 25* 6X6*
CFSTATUS	=	ENGINEERING RESTRICTED AVAILABLE
TARGNAME	=	BIAS DARK
OBSMODE	=	ACQ ACQ/PEAK

* wildcard; != not equal to

3. Details of Processing Steps

The extraction of 1-D spectra from the flat-fielded (or CR-rejected) two-dimensional input image is a multistage process that is summarized in Figure 1. At each step in the processing, *calstis6* requires specific information that is read either from the input file headers, or from the calibration reference files. Table 2 summarizes the input data and their sources required by *calstis6* for the various processing steps. Figure 2 depicts a representative spectrum (first-order or single echelle order) in a hypothetical point-source input image, and provides the definition of the coordinate system used throughout this report.

We note that the pixel-based processing in the *calstis6* code is always performed using *zero-indexed arrays*, and usually using *reference pixels*, while input and output pixel-based information is in *image pixels in one-indexed arrays*. Reference tables use *reference pixels in one-indexed arrays*. The mapping between reference pixels and image pixels is described in detail in STIS ISR 98-26 (Hodge et al. 1998).

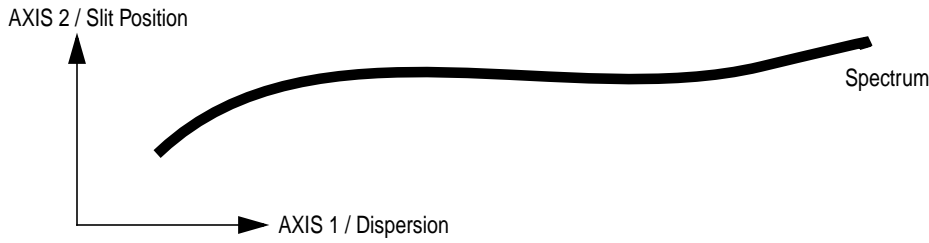
Calstis6 performs two iterative loops during processing. The first loop is over all imsets in the input data file, and includes all steps (3.1-3.6) shown in Figure 1 and detailed below. All iterations through the first loop produce a unique binary table extension in the output (*_x1d.fits or *_sx1.fits) file. The second loop is over all spectral orders within a particular imset, and includes steps 3.2-3.6 below. Spectral orders which have DUMMY or nonexistent matching rows in the reference tables are skipped in the *calstis6* processing. The output of each iteration through spectral order is a separate row in the binary table extension corresponding to the input imset.

Table 2. Required input data and its source for *calstis6* processing.

Keyword	Source	Description
OPT_ELEM APERTURE CENWAVE	Input file/primary header	The optical element, aperture and central wavelength used for the observation.
MOFFSET1 MOFFSET2	Input file/primary header	Commanded offsets for MAMA observations to reduce degradation of MAMA detectors.
SHIFTA1 SHIFTA2	Input file/extension header	Offset determined from the associated WAVECAL processing, caused by thermal drifts and the limits of the MSM repeatability.
A1CENTER A2CENTER	SPTRCTAB	Nominal spectrum location.
A2DISPL	SPTRCTAB	Distortion vector (spectrum “trace”).
MAXSRCH	XTRACTAB	Cross correlation search range.
EXTRSIZE	XTRACTAB	Size of extraction box in pixels.
BK1SIZE BK2SIZE	XTRACTAB	Size of background extraction boxes in pixels.
BK1OFFST BK2OFFST BKTCOEFF*	XTRACTAB	Offsets of the two background extraction boxes. Coefficients describing the tilt of the background extraction boxes.
BACKORD	XTRACTAB	Order of the polynomial fit to background.
XTRCALG	XTRACTAB	Algorithm for extraction.

* Note that BKTCOEFF has replaced an older parameter called BKTILT, which is now obsolete but is still found in old XTRACTAB reference files.

Figure 2: The STIS coordinate system for spectroscopic observations



3.1 Read the input data and XTRACTAB

The input data consist of a flat-fielded (`*_flt.fits`) or cosmic ray rejected (`*_crj.fits`) 2-D science image. In addition to reading the input image data, *calstis6* reads primary header keywords from the input image that describe the instrument configuration: DETECTOR, OPT_ELEM, APERTURE, and CENWAVE. These keywords are, in turn, used to select the appropriate calibration data from the calibration reference tables. Figure 1 lists the set of calibration switch keywords that controls calibration processing and the keywords containing the names of the supporting calibration reference tables used in the processing. In this step, the values of OPT_ELEM and CENWAVE are used to select all matching rows of the XTRACTAB (`*_ldx.fits`) reference table, and the spectral order (SPORDER) values for each matching row are used to determine the range of spectral orders to be extracted from the input image. The loop over SPORDER then proceeds from the minimum to the maximum values of this range.

3.2 XIDCORR: Locate and extract 1-D Spectra

In the pipeline, *calstis0* determines if *calstis6* should be called based on the value of the XIDCORR calibration switch.

Locate the spectrum

The nominal location and shape (called the spectrum “trace”) of the spectrum to be extracted are specified in the spectrum trace table (SPTRCTAB, `*_ldt.fits`). The exact structure of this table is detailed in Section 6, Table 6. The nominal location of the center of the spectrum is given by the (A1CENTER, A2CENTER) values from this table, which are not constrained to be integers. Based on the values of OPT_ELEM, CENWAVE, and SPORDER, all matching rows of the table are read into memory. For echelle observations, there is currently only one matching row in the SPTRCTAB for each SPORDER. For non-echelle data there are many matching rows with different A2CENTERS (i.e., different possible Y positions of the spectrum on the detector). Data from the *first* of these matching rows is used as an initial guess, and the actual trace used is refined later. The

description of the distorted shape of the spectrum is stored in the SPTRCTAB column A2DISPL as a vector consisting of pixel offsets (in the AXIS2 direction) relative to the nominal center of the spectrum (A2CENTER). This spectrum trace is used to find (and eventually to extract) the 1-D spectrum.

Several known shifts of the spectrum location are then accounted for in the processing. The first is a commanded offset for MAMA observations that changes monthly to reduce the degradation of the detectors by preventing spectra from falling at the same place on the detector for extended periods of time. The values of the commanded offset are found in the input file primary header keywords (MOFFSET1,MOFFSET2). The second of the known shifts is that determined from processing of the associated WAVECAL (*_wav.fits) data file. This shift is caused by thermal drifts and the MAMA Mode Select Mechanism non-repeatability. Details of the WAVECAL processing are given in STIS ISR 98-12 (Hodge et al. 1998). The WAVECAL processing shift is written to the extension header keywords (SHIFTA1,SHIFTA2) of the basic 2-D processing output file (*_flt.fits or *_crj.fits), which is the input file for *calstis6*. In subsequent processing, the value of these keywords is read from the SCI extension headers.

The exact location of the spectrum is then improved by “searching” in the vicinity of the nominal location by performing a cross-correlation between the distortion vector and the input spectrum image. Figure 3 on page 7 schematically shows the cross correlation process. The search extends for $\pm n$ pixels around the nominal spectrum center, where n is read from the MAXSRCH column in the XTRACTAB table. At each AXIS2 position in the search range (which differs from the nominal center by an integer number of pixels) a sum of the counts along the spectrum shape is formed. This sum is created by adding the value of one pixel’s worth of data at each of the AXIS1 pixel positions. The pixel extracted in the AXIS2 direction is centered on the spectrum position (A2CENTER + pixel offset) and may include fractional contributions from two pixels, which are weighted by the fractional area. Quadratic refinement using the highest sum and its two nearest neighbors (as shown in Figure 4 on page 8) is used to locate the spectrum to a fraction of a pixel. After the cross correlation search, but before the spectrum is extracted, *calstis6* uses the refined location of the spectrum to find the best A2DISPL vector from the matching rows of the SPTRCTAB (read into memory earlier) by interpolating between the two nearest (in A2CENTER) traces (recall that the first matching row of the SPTRCTAB was used initially to determine the nominal A2CENTER and A2DISPL).

A global cross correlation algorithm is used to find the positions of spectral orders that fail to produce a meaningful cross correlation solution. Before attempting to extract individual spectral orders for echelle data *calstis6* tries to find the cross correlation offsets for all spectral orders in the image. The ones that fail to produce a meaningful result are flagged, and at the time of actual extraction the program uses the average cross correlation offset (CRSCROFF) over all good orders to extract the flagged orders.

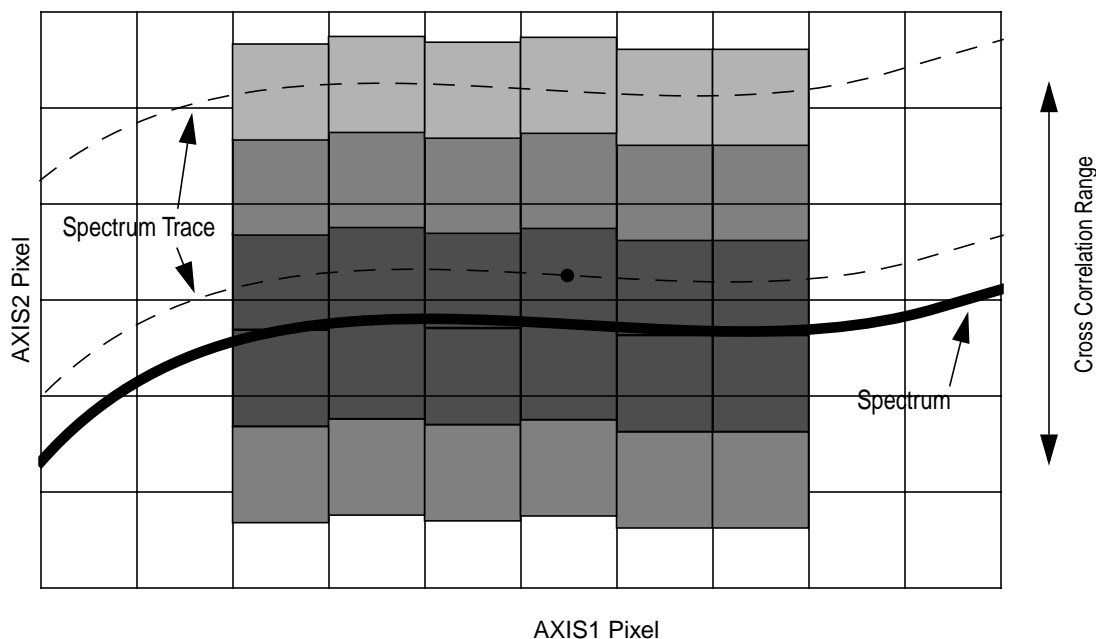
The final Y location of the extracted spectrum is (in image pixels):

$$EXTRLOCY(i) = [(A2CENTER - 1.0) + MOFFSET2 + SHIFTA2 + OFFSET + A2DISPL(i)] \times LTM + LTV + 1.0$$

where OFFSET is the offset found during the cross correlation search. If the cross correlation fails, the value of OFFSET is set to zero (for first order) or CRSCROFF (for echelle), and a warning message is written to the trailer (*_trl.fits) file. The EXTRLOCY array, and the final values of OFFSET and A2CENTER for the extracted spectrum, are written to columns in the output file (see section 5 for further details). For echelle spectroscopy, the average value of the OFFSET over all spectral orders (CRSCROFF) is written to the output extension header. For 1st-order spectroscopic observations, since only one spectrum is extracted, CRSCROFF = OFFSET. The extraction position is also reported in the standard output (*_trl.fits) file.

It is important to note that for 1st-order spectroscopy the MAXSRCH value is 1024, so the *entire image* is searched in the cross correlation refinement. Thus the brightest target (or trace location) in the entire image is located, and *this may not necessarily correspond to the target spectrum*, especially in long-slit spectroscopy or spectroscopy of extended objects.

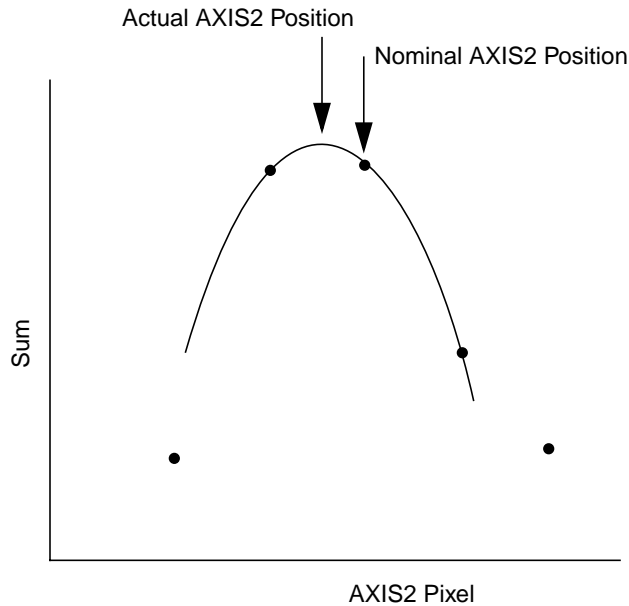
Figure 3: . Cross Correlation for “Finding” Spectrum Center



Extract the 1-D spectra

Extraction of the 1-D spectrum is driven by the parameters in the XTRACTAB (*_ldx.fits) reference table. The description of the columns in the XTRACTAB reference file are detailed in Section 6, Table 7. The table is read to find all rows for which the values of APERTURE, OPT_ELEM and CENWAVE match the values in the input image header. *Calstis6* tries to extract all spectral orders that match the criteria above. Only spectral orders that actually fall on the detector are extracted; the others are skipped and a warning message is printed in the trailer (*_trl.fits) file. The extraction of the spectrum, shown schematically in Figure 6 on page 10, is defined by a triplet of extraction “boxes,” one for the spectrum, and two for the background, found in the XTRACTAB reference table. Figure 6 on page 10 shows a schematic representation of the extraction boxes. For each pixel in the dispersion direction, *calstis6* sums the values in the spectrum extraction box. (Remember that we determined the center of the spectrum in the previous step.) The extraction box is one pixel wide and EXTRSIZE pixels tall (currently 7 and 11 pixels for echelle and first-order spectra respectively), centered on the spectrum. The spectrum extraction box is not tilted. The height of the extraction box may include a fractional part of one or two pixels, in which case *calstis6* scales the counts in the given pixel by the fraction of the pixel extracted. Thus, each pixel in the output spectrum consists of the sum of some number (or fraction) of pixels in the input image. The background extraction boxes are one pixel wide,

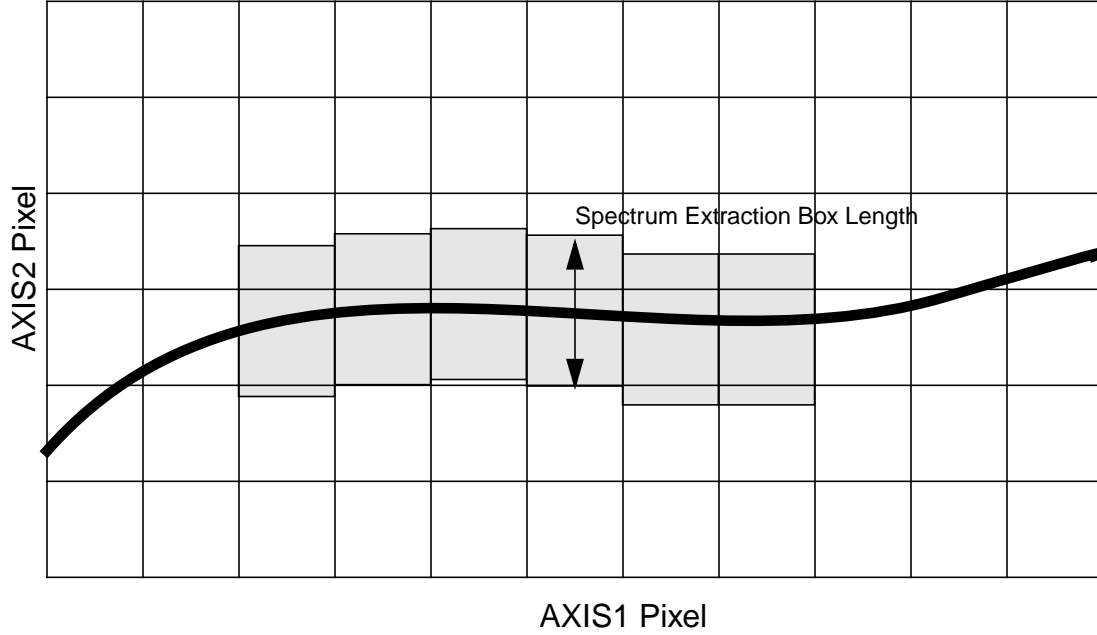
Figure 4: Quadratic Refinement Used to “Find” Actual AXIS2 Center of Spectrum



and BK1SIZE/ BK2SIZE tall, and their centers are offset in the AXIS2 direction by BK1OFFST/BK2OFFST from the center of the spectrum. The background boxes can be

curved, with the curvature determined by a polynomial with coefficients BKTCOEFF. Therefore, the centers of the pixels composing the background box follow the line of curvature even though the pixels themselves are rectilinear (see Figure 6).

Figure 5: Extracting the 1-D Spectrum.



The extraction of the spectrum allows for unweighted or optimal extraction. The extraction algorithm is selected based on the value of the reference table parameter XTRACALG. This flag has possible values of UNWEIGHTED and OPTIMAL. Pipeline processing performs only unweighted extraction, while optimal extraction is currently implemented for use in the *calstis6* stand-alone IRAF task **x1d**. There are no plans to perform optimal extraction in the pipeline in the near future.

Extraction of one-dimensional spectra for point sources can be described by:

$$N_{\lambda} = \frac{\sum_s W_{s\lambda} (C_{s\lambda} - B_{s\lambda})}{\sum_s W_{s\lambda}} \quad \text{(Equation 1)}$$

where

N_{λ} is the net extracted spectrum,

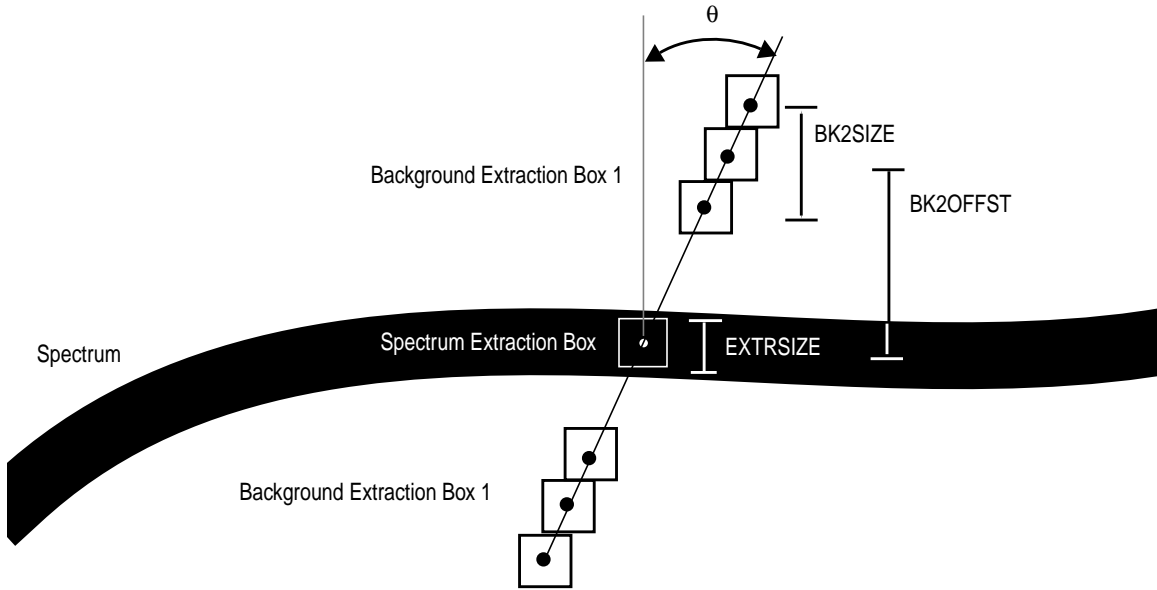
$W_{s\lambda}$ is the weighting applied to each pixel in the spectrum,

$C_{s\lambda}$ is the observed count rate at each slit position and wavelength, and

$B_{s\lambda}$ is the fitted background (and/or sky) count rate at each slit position and wavelength.

In the case of unweighted extraction, the factor $W_{s\lambda}$ has the value of 1 at every pixel in the spectrum and is 0 outside of the spectrum. In the case of fractional pixels, $W_{s\lambda}$ is the fractional pixel size, which occurs at the two ends of the extraction box. A rectangular extraction box centered in the slit direction on the spectrum is used to identify that portion of the 2-D spectrum to be summed to produce the output 1-D spectrum.

Figure 6: Extraction Box Geometry



3.3 BACKCORR: Subtract the Background

If the calibration switch BACKCORR has the value of “PERFORM”, the background is calculated and subtracted from the extracted spectrum. The background is extracted using two background extraction boxes located above and below the spectrum by BK1OFFST, BK2OFFST, and a function is fit to the background. The fitting function is restricted to a zeroth or first order polynomial fit and is a function of the AXIS2 position. The polynomial order, BACKORD, is read from the XTRACTAB table. It currently has a value of 0 in all XTRACTAB reference tables. Average background (c/s/pixel) values are calculated from each background bin, with complete accounting of the fractional pixel contributions to the background. In the case of BACKORD=0, a simple average of the two background bins is computed. For BACKORD=1, a linear fit to the background values as a function of AXIS2 position is computed. A background value is then interpolated at the center of each pixel that contributes to the extracted spectrum. The background in the spectrum extraction box is totaled and subtracted from the sum of the spectrum box. The

total background at each pixel in the output spectrum is saved and eventually written out to the output data file (see Section 5 below for further details). In general, it is not assumed that the background or sky is aligned with the detector pixels. To accommodate this the definition of the background extraction apertures includes not only a length and offset (center-to-center), but also a tilt determined by the coefficients `BKTCOEFF`, to assist in properly subtracting the background. The tilt angle from the `AXIS2` direction is a function of the pixel position in the `AXIS1` direction:

$$\theta = \sum_{i=0}^{NBKCOEFF-1} BKTCOEFF(i+1) \times x^i$$

where x is the `AXIS1` position of the spectrum extraction box (see Figure 6). In practice, all `BKTCOEFF` values are currently zero except the $i=1$ term, so at present the tilt does not change with `AXIS1` position in the pipeline. The `AXIS1` and `AXIS2` projection factors, $\sin \theta$ and $\cos \theta$, are then computed for use in determining the `AXIS1` and `AXIS2` pixel location of the background box pixels.

All pixels in the input image are used for both extraction and background computations, regardless of their DQ values, i.e., the `SDQFLAGS` keyword in the input file is not used as a mask against each pixel's DQ flag. The background is fitted using up to 5 sigma-clip iterations. If more than 30% of the background pixels are rejected, the 11th bit in the output DQ array is set. [For a more detailed explanation of data quality flagging see section 20.5.2 of the *HST Data Handbook*, version 3.] Any portion of a background region not on the detector (which could easily happen in extraction of 1st-order spectra) is included in the rejected pixel count.

3.4 DISPCORR: Assign Wavelengths

Wavelengths are assigned using dispersion coefficients from the reference table `DISPTAB (*_dsp.fits)` when the calibration switch `DISPCORR` is set to "PERFORM." Offsets introduced by using apertures other than a reference aperture (used to derive the coefficients) are removed using coefficients in the `INANGTAB (*_iac.fits)` reference table. Offsets introduced by the monthly MAMA dither offsets are removed using coefficients in the `MOFFTAB (*_moc.fits)` table. The contents of these reference files are detailed in section 6, Tables 8, 9, and 10.

The `DISPTAB` table contains coefficients for fits to the following dispersion solution:

$$s = A_0 + A_1 m \lambda + A_2 (m \lambda)^2 + A_3 m + A_4 \lambda + A_5 m^2 \lambda + A_6 m \lambda^2$$

(Equation 2)

where

λ is the wavelength in Angstroms,

s is the detector AXIS1 position,

m is the spectral order, and

A_i are the dispersion coefficients.

A wavelength is calculated for each pixel in the AXIS1 direction. First, any modification to the dispersion coefficients due to spectrum offsets must be made. Table 3 on page 12 lists the possible offsets and the appropriate corrections. The dispersion relation (Equation 2) gives the pixel number as a function of wavelength and spectral order while *calstis6* needs the wavelength as a function of pixel number for a given spectral order. The wavelength value is solved for iteratively using the Newton-Raphson method (see, for example, Press, W.H. et al. *Numerical Recipes in C*. 1992. p. 362).

Table 3. Modifications to the Dispersion Coefficients Caused by Offsets

Correction	Ref Table	Algorithm	Definitions
Incidence Angle	INANGTAB	$A_i = A_i + c1_i s$ $A_0 = A_0 + c2_1 s + c2_2 s^2$	A_i dispersion coefficients $c1, c2$ incidence angle coefficients s aperture offsets in the axis 1 direction calculated as difference of relative aperture centers (arcsec)
MAMA Offsets	MOFFTAB	$A_i = A_i + o1_i x1 + o2_i x2$	A_i dispersion coefficients $o1, o2$ MAMA offset coefficients $x1 = \text{MOFFSET1}$ (pixels) $x2 = \text{MOFFSET2}$ (pixels)
MSM Offset		$A_0 = A_0 + \text{SHIFTA1}$	A_i dispersion coefficients SHIFTA1 from extension header keyword

3.5 HELCORR: Apply heliocentric corrections to the wavelengths

The correction of wavelengths to a heliocentric reference frame is controlled by the calibration switches HELCORR and DISPCORR—if both switches are 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.

$$\lambda_{helio} = \lambda_{obs} \left(1 + \frac{v}{c} \right) \quad \text{(Equation 3)}$$

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 calculate the velocity vector of the earth in the equatorial coordinate system of the epoch J2000. The algorithm does not include Earth-Moon motion, Sun-barycenter 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.) The algorithm used to perform heliocentric velocity correction is identical in *calstis6* and *calstis7* (which performs 2-D rectification; see ISR 98-13, McGrath et al. 1998).

3.6 FLUXCORR: Convert to absolute flux

If FLUXCORR is set to "PERFORM", the raw counts are converted to absolute flux ($\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$) using the reference files PHOTTAB (*_pht.fits) and APERTAB (*_apt.fits). Execution of the flux conversion calibration step requires that wavelengths have been assigned. Corrections for vignetting and echelle blaze are handled within the PHOTTAB reference files. No attempt has been made to decouple all of the various sources of response variation seen with STIS. The conversion to absolute flux is calculated as:

$$F_{\lambda} = \frac{hcGHC_{\lambda}}{A_{HST}T_{\lambda}^{sys}T_{\lambda}^{ap}\lambda d} \quad (\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}) \quad (\text{Equation 4})$$

F_{λ} is the calibrated flux at a particular wavelength,

h is Planck's constant,

c is the speed of light,

C_{λ} is the net count rate at a particular wavelength,

G is the analog to digital gain (CCD only; $G=1$ for MAMA),

A_{HST} is the area of the unobstructed HST primary mirror ($\pi \cdot 120^2 = 45238.93416 \text{ cm}^2$),

T_{λ}^{sys} is the integrated system throughput (including OTA) at a particular wavelength for infinite extraction box height, as delivered in the PHOTTAB reference table,

T_{λ}^{ap} is the aperture throughput at a particular wavelength, from the APERTAB reference table,

λ is a particular wavelength,

d is the dispersion ($\text{\AA}/\text{pixel}$) at a particular wavelength,

H is a correction factor accounting for the finite extraction box height (EXTRSIZE) used to extract the spectra; H is the ratio of throughput for an infinite extraction box height divided by the throughput for the extraction box height used to extract the spectrum, where the throughputs are taken from the PCTAB (*_pct.fits) reference table.

4. Data Quality and Error Propagation

Data Quality Propagation

The data quality value for any pixel in an extracted 1-D spectrum is the “or-ed” value of all data quality values that were used to produce the spectrum. As noted in section 3.3 above, the background is fitted using up to 5 sigma-clip iterations. If more than 30% of the background pixels are rejected, the 11th bit (2048) in the output DQ array is set. The 12th bit (4096) of the output DQ array is currently not set in *calstis6*.

Error Propagation

Calstis6 will propagate errors during the conversion of counts to count rate, the extraction of the 1-D spectra, the subtraction of the background, and the conversion to absolute flux. In those cases where fractional pixels are coadded to form a sum, the relative error from each fractional part is combined to form the error associated with the sum. The errors associated with the calibrated data are part of the output data products. These errors are consistent with the highest level of flux calibration applied to the data (i.e., if the data are only processed as far as background subtracted count rates, the error estimates are those associated with the count rate values). In equations 5-7 below, the delta (Δ) terms represent the associated errors for a given measurement.

The gross count rate spectrum is calculated as:

$$C \pm \Delta C = \frac{R}{t} \pm \frac{\Delta R}{t} \quad \text{(Equation 5)}$$

$C \pm \Delta C$ is the count rate,

$R \pm \Delta R$ is the raw counts, and

t is the exposure time.

The net spectrum is calculated as:

$$N \pm \Delta N = (C - B) \pm (\Delta C^2 + \Delta B^2)^{1/2} \quad \text{(Equation 6)}$$

$N \pm \Delta N$ is the net spectrum and

$B \pm \Delta B$ is the background.

The flux calibrated spectrum is calculated as:

$$F \pm \Delta F = N \times S \pm (\Delta N \times S) \quad \text{(Equation 7)}$$

$F \pm \Delta F$ is the flux calibrated spectrum and

$$S = \frac{hcGH}{A_{HST} T_{\lambda}^{sys} T_{\lambda}^{ap} \lambda d} \quad \text{is the flux conversion factor (see Equation 4).}$$

5. Output Data (*_x1d.fits or *_sx1.fits)

One spectrum is written to one row of a FITS binary table extension. A complete spectrum consists of seven arrays containing: wavelengths, gross count rates, background count rates, net count rates, absolute fluxes, absolute flux error estimates, and data quality flags. Each row also contains columns describing the spectral order, number of data points in the spectrum (NELEM), and information about the exact location of the extracted spectrum and background boxes, as detailed in sections 3.2 and 3.3 above. Table 4 summarizes the structure of the FITS files created by *calstis6*. The mapping is effectively one output table extension to each input group of image extensions (imset), and each row of a binary table extension corresponds to a distinct spectral order within the imset. Table 5 lists the table column labels, units, and datatypes for the output (*_x1d.fits or *_sx1.fits) file. If the output table is empty, a warning message is written to the trailer (*_trl.fits) file, and no output file is produced.

Table 4. Output spectrum FITS definition

Output	Source
Primary header	Primary header copied from input science data file
Primary data	empty
1st binary table extension header	definition of binary table PLUS copy of extension header from 1st input science extension [sci,1]
1st table extension data	extracted spectra from 1st science extension
nth binary table extension header	definition of binary table PLUS copy of extension header from nth input science extension [sci,n]
nth table extension data	extracted spectra from nth science extension

Table 5. Column Definitions for Output Binary Table (*_x1d.fits or *_sx1.fits)

Column Name	Datatype	Units	Description
SPORDER	I*2		Spectral order
NELEM	I*2		Number of array elements
WAVELENGTH	R*8[n]	Angstroms	Wavelength array [n=NELEM]
GROSS	R*4[n]	counts/sec	Gross count rate
BACKGROUND	R*4[n]	counts/sec	Background count rate
NET	R*4[n]	counts/sec	Net count rate
FLUX	R*4[n]	$\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$	Absolute flux
ERROR	R*4[n]	$\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$	Error array
DQ	I*2[n]		Data Quality flags
A2CENTER	R*4	pixel	AXIS2 location of the extracted spectrum
EXTRSIZE	R*4	pixel	Size of spectrum extraction box
MAXSEARCH	I*2	pixel	Cross correlation search range
BK1SIZE	R*4	pixel	Size of first background extraction box
BK2SIZE	R*4	pixel	Size of second background extraction box
BK1OFFST	R*4	pixel	Offset of 1st background box from A2CENTER
BK2OFFST	R*4	pixel	Offset of 2nd background box from A2CENTER
EXTRLOCY	R*4[n]	pixel	Array of AXIS2 extraction location for each pixel of the extracted spectrum
OFFSET	R*4	pixel	Offset of actual A2CENTER from nominal A2CENTER

6. Calibration Reference Files and Tables

Below are listed the calibration reference tables used by *calstis6*. Only those columns used by *calstis6* are included. For more details on the reference tables refer to ICD-47.

Table 6. SPTRCTAB (*_1dt.fits) – 1-D Spectrum Trace Table

Column Name	Data Type	Units	Description
OPT_ELEM	C*8		optical element in use
CENWAVE	I*2	Angstrom	central wavelength
SPORDER	I*2		spectral order

Column Name	Data Type	Units	Description
NELEM	I*2		number of data points in spectrum
A2DISPL	R*4[1024]	pixel	displacement along axis2
A1CENTER	R*4	pixel	nominal axis 1 coordinate of center of spectrum
A2CENTER	R*4	pixel	nominal axis 2 coordinate of center of spectrum

Table 7. XTRACTAB (*_1dx.fits) – 1-D Extraction Parameter Table

Column Name	Data Type	Units	Description
APERTURE	C*16		aperture in use
OPT_ELEM	C*8		optical element in use
CENWAVE	I*2	Angstrom	central wavelength
SPORDER	I*2		spectral order
EXTRSIZE	R*4	pixel	size of spectrum extraction box
BK1SIZE	R*4	pixel	size of background extraction box #1
BK2SIZE	R*4	pixel	size of background extraction box #2
BK1OFFST	R*4	pixel	offset of background extraction box #1 from spectrum extraction box
BK2OFFST	R*4	pixel	offset of background extraction box #2 from spectrum extraction box
NCOEFFBK	I*2		number of background coefficients BKTCOEFF
BKTCOEFF*	R*8[8]	degrees	angle of background extraction boxes w.r.t. axis2
BACKORD	I*2		order of polynomial fit to background
XTRACALG	C*12		extraction algorithm
MAXSRCH	I*2	pixel	maximum search size for cross correlation

*Note that BKTCOEFF has replaced an older parameter called BKTILT, which is now obsolete but is still found in old XTRACTAB reference files.

Table 8. DISPTAB (*_dsp.fits) – Dispersion Coefficients Table

Column Name	Data Type	Units	Description
OPT_ELEM	C*8		optical element in use
CENWAVE	I*2	Angstrom	central wavelength
SPORDER	I*2		spectral order

Column Name	Data Type	Units	Description
REF_APER	C*12		reference aperture
A2CENTER	R*4	pixel	nominal axis2 coordinate for center of spectrum
NCOEFF	I*2		number of coefficients in dispersion solution
COEFF	R*8[10]		dispersion solution coefficients

Table 9. INANGTAB (*_iac.fits) – Incidence Angle Correction Table

Column Name	Data Type	Units	Description
OPT_ELEM	C*8		optical element in use
CENWAVE	I*2	Angstrom	central wavelength
SPORDER	I*2		spectral order
NCOEFF	I*2		number of coefficients in IAC solution for both terms
COEFF1	R*8[10]		incidence angle correction coefficients for first term
COEFF2	R*8[10]		incidence angle correction coefficients for second term

Table 10. MOFFTAB (*_moc.fits) – MAMA Offset Correction Table

Column Name	Data Type	Units	Description
OPT_ELEM	C*8		optical element in use
CENWAVE	I*2	Angstrom	central wavelength
SPORDER	I*2		spectral order
NCOEFF1	I*2		no. coefficients in MAMA offset solution for first term
COEFF1	R*8[8]		MAMA offset correction coefficients for first term
NCOEFF2	I*2		no. coefficients in MAMA offset solution for second term
COEFF2	R*8[8]		MAMA offset correction coefficients for second term

Table 11. APDESTAB (*_apd.fits) – Aperture Description Table

Column Name	Data Type	Units	Description
APERTURE	C*16		aperture in use
OFFSET1	R*4	arcsec	offset from nominal position in axis1
OFFSET2	R*4	arcsec	offset from nominal position in axis2

Table 12. APERTAB (*_apt.fits) – Aperture Throughput Table

Column Name	Data Type	Units	Description
APERTURE	C*16		aperture in use
NELEM	I*2		number of data points in throughput array
WAVELENGTH	R*8[10000]	Angstrom	reference wavelength
THROUGHPUT	R*8[10000]		total system throughput at each wavelength

Table 13. PHOTTAB (*_pht.fits) – Photometric Conversion Table

Column Name	Data Type	Units	Description
OPT_ELEM	C*8		optical element in use
CENWAVE	I*2	Angstrom	central wavelength
SPORDER	I*2		spectral order
NELEM	I*2		number of data points in throughput array
WAVELENGTH	R*8[500]	Angstrom	reference wavelength
THROUGHPUT	R*4[500]		total system throughput at each wavelength
ERROR	R*4[500]		error associated with THROUGHPUT

7. References

Hodge, Phil, Stefi Baum, Melissa McGrath, Steve Hulbert, Jennifer Christensen, and the Spectrographs Group Pipeline Block. “Calstis4, calstis11, calstis12: Wavecal Processing in the STIS Calibration Pipeline” STIS ISR 98-12, April 1998.

Hodge, Phil, Stefi Baum, and Paul Goudfrooij. “Calstis1: Basic Two-dimensional Image Processing” STIS ISR 98-26, October 1998.

Hulbert, Steve, Phil Hodge, and Ivo Busko. “The STScI STIS Pipeline VII: Extraction of 1-D Spectra” STIS ISR 97-02, February 1997.

McGrath, Melissa A., Phil Hodge, Stefi Baum and the Spectrographs Group Pipeline Block. “Calstis7: Two-dimensional rectification of spectroscopic data in the STIS Calibration Pipeline” STIS ISR 98-13, May 1998.