

STIS Data Analysis

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In this chapter we discuss the data reduction applications available to work with STIS data, and describe specific analyses you may want to apply to your spectral, timetag, and acquisition data.

23.1 Data Reduction Applications

Most of the *new* software tools for operating on STIS FITS files are contained in two STSDAS packages:

- **toolbox.imgtools.mstools**: Contains image manipulation tasks created especially for STIS and NICMOS image set (*imset*) data and which exploit the error and data quality arrays in their operations (e.g., **msarith**, **mscombine**, **msstatistics**, **mssplit**, and **msjoin**). These tasks are described in “Working with STIS and NICMOS Imsets” on page 3-12.
- **hst_calib.stis**: Contains the STIS specific tasks including **basic2d**, **calstis**, **inttag**, **ocrreject**, **odelaytime**, **wavecal**, **x1d**, and **x2d**.

In addition to the above packages, most basic image manipulation software (e.g., **display**, **daophot**, **imexamine**, **contour**, etc.) and spectral analysis software (e.g., **splot**, **tables**, **specfit**, **igi**, etc.) available in IRAF/STSDAS can be used on STIS data, either directly through the IRAF FITS interface or by converting data to another IRAF format. Chapter 3 includes information about how to display STIS images and extracted spectra as well as how and when to convert data formats and a description of spectral analysis tasks. Table 23.1 lists some of the more useful IRAF/STSDAS applications for working with STIS data.

Table 23.1: Spectral Analysis Tasks

Task	Input Formats	Purpose
echplot	3-D tables	Plots multiple STIS echelle spectral orders.
nfit1d	2-D & 3-D tables, images	General 1-D feature fitting; part of the STSDAS fitting package.
igi	2-D & 3-D tables, images	General presentation graphics; supports world coordinates.
sgraph	2-D & 3-D tables, images	General 1-D plotting; supports world coordinates.
specfit	1-D images, ASCII tables	General 1-D spectrum modeling package.
splot	<i>multispec</i> images	General 1-D spectral analysis.

Some of the tasks are intended for browsing data or producing publication-quality plots: the **igi** and **sgraph** tasks were described in Chapter 3. The **echplot** task is useful for browsing STIS extracted spectra. You can plot single spectral orders, overplot multiple orders on a single plot, or plot up to 4 orders in separate panels on the same page. For example, we overplot the orders contained in rows 2 through 4 and 6 on one page:

```
cl> echplot "stis_xld.fits[1][r:row=(2:4,6)]" output.igi \
>>> plot_style=m
```

Note that the `plot_style` parameter governs whether the spectral orders are plotted one per page, overplotted, or plotted one per panel, for parameter values of “s”, “m”, or “p” respectively. The brightness unit is calibrated FLUX by default, though other quantities (e.g., NET counts) can be specified using the `flux_col` parameter.

23.2 STIS-Specific Reduction and Analysis Tasks

In Chapter 21 we discussed the components of the STIS pipeline that can be run as individual tasks. Observers may find that they wish to perform parts of the pipeline reduction again on their data using these tasks. Typical examples will be to re-perform cosmic ray rejection, altering the input parameters or using data from separate datasets, or to perform one-dimensional spectral extraction on long-slit data or to modify the input parameters (e.g., aperture extraction box, or background region) when doing one-dimensional spectral extraction for echelle data. For completeness we list the tasks again below. To run these tasks you need to retrieve the calibration reference files they require from the Archive and set the `oref` parameter appropriately (see “Mechanics of Full Recalibration” on page 21-30). An example of using **x1d** with a user specified extraction box (11 pixels high) and a user specified center (line=500) is given below:

```
cl> x1d stis_flt.fits stis.fits center=500 size=11
```

Table 23.2 lists some of the stand-alone tasks for working with STIS data. Consult the on-line help for more information about all these tasks. We expect additional options to become available within the distributed versions of these tasks as we add additional control parameters, and new functionality. Planned features for **x1d** include background subtraction for echelle modes and an optimal-weighted extraction for echelle and first-order spectra.

Table 23.2: STIS-Specific Tasks

Task	Description
basic2d	Perform basic 2-D calibration.
inttag	Integrate TIMETAG event list to form an image.
ocrreject	Combine images, rejecting cosmic rays.
wavecal	Process wavecal images, determine spectral and spatial shifts.
x1d	Extract 1-D spectrum.
x2d	Rectify spectral images.

23.3 Working with Two Dimensional Extracted Spectra

Sensitivity Units and Conversions

Your two dimensional extracted spectrum (**_sx2**, or **_x2d** file) has units of $\text{erg cm}^{-2} \text{sec}^{-1} \text{\AA}^{-1} \text{arcsec}^{-2}$. The conversion from counts to surface brightness (I_λ) is calculated by the pipeline as:

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

where

- C_λ is the wavelength-dependent count rate, which is the ratio of the total counts to the exposure time. The exposure time is given in the EXPTIME header keyword.
- G is the detector gain, which is unity for MAMA observations. For the CCD, this is the conversion from counts to electrons, the value for which is given in the header keyword ATODGAIN.
- h is Planck's constant.
- c is the speed of light.
- T_λ^{sys} is the wavelength-dependent integrated system throughput divided by the area of the unobstructed HST mirror, which is given in the PHOTAB reference file table.

- A_{HST} is the area of the unobstructed HST mirror.
- d is the dispersion in Å/pixel, derived from the CD1_1 header keyword.
- m_s is the plate scale in arcseconds/pixel in the cross-dispersion direction, which is the product of the CD2_2 header keyword value and (3600 arcsec/degree).
- W is the slit width in arcseconds.
- λ is the wavelength in Angstroms.

The flux from a fully extended continuum source as transmitted by the science slit, over an arbitrary number of pixels in the spatial direction (Npix_s) and taken over an arbitrary number of pixels in the wavelength direction (Npix_λ)¹, is given by:

$$\mu(I_\lambda) \times W \times \text{Npix}_s \times m_s$$

in units of ergs/cm²/sec/Å, where:

- $\mu(I_\lambda)$ is the average value of the surface brightness, I_λ , over the $\text{Npix}_s \times \text{Npix}_\lambda$ pixels in the rectangle being integrated.

For an emission line source, the situation is somewhat different. There, the line surface brightness, I_{line} , from an emission line feature, in ergs sec⁻¹ cm⁻² arcsec⁻² is given as:

$$I_{\text{line}} = \frac{C_\lambda \times G \times h \times c}{(T_\lambda^{\text{sys}} \times t_\lambda \times A_{\text{HST}} \times m_s \times m_\lambda \times \lambda)} = I_\lambda \times (W \times d / m_\lambda)$$

where:

- I_λ is as given above (i.e., the values in the _x2d or _sx2 image).
- m_λ is the plate scale (in arcsec/pixel) in the dispersion direction as given in the SCALE_A1 header keyword.
- All other parameters are as above.

Having performed this conversion, one can take an average or sum of the value of I_{line} over the extent of a feature to get the mean, $\mu(I_{\text{line}})$, or to get the total flux from the line:

$$F_{\text{line}} = \mu(I_{\text{line}}) \times \text{Npix}_\lambda \times m_\lambda \times \text{Npix}_s \times m_s$$

over a $\text{Npix}_\lambda \times m_\lambda$ by $\text{Npix}_s \times m_s$ region on the sky, where $\text{Npix}_\lambda \times m_\lambda$ equals the width of the emission feature in the spectral direction.

The factor $W \times d / m_\lambda$ converts between diffuse continuum source surface brightness and diffuse emission line surface brightness and is given in the CONT2EML header keyword; it is simply the slit width expressed in Angstroms.

1. To keep from degrading the spectral purity $\text{Npix}_\lambda \times m_\lambda$ must be less than W .

The solid angle of a pixel in arcsec² ($m_s \times m_\lambda$) is given in the header keyword OMEGAPIX.

Finally, the DIFF2PT keyword in the data header gives the conversion factor to flux units in erg cm⁻² sec⁻¹ Å⁻¹ for a point source. The DIFF2PT keyword is calculated as:

$$DIFF2PT = \frac{W \times m_s \times H_\lambda(h)}{T^{ap}}$$

where W and m_s are as above, T^{ap} is the wavelength-averaged point-source aperture throughput for the science aperture (which is determined from the reference table specified by the keyword APERTAB), and $H_\lambda(h)$ is the wavelength-dependent correction for the extraction slit of height h to a slit of infinite height, which is obtained from the reference table specified by the keyword PCTAB. That is, to derive the flux from a point source, integrate the `_x2d` or `_sx2` file over the default extraction slit height (from the PCTAB) and multiply the result by DIFF2PT. The default extraction slit height for first-order modes is at present 11 pixels for the MAMAs and 7 pixels for the CCD. If the desired extraction slit height differs from the default, the PCTAB has a set of wavelength-dependent corrections for selected alternative apertures that must also be applied. See *STIS ISR 98-01* for further details. Of course, point source observers are better advised to use the **x1d** task to extract a one-dimensional spectrum from their long-slit first-order data, which will then apply the wavelength-dependent aperture throughput, the defined point source extraction aperture and calibration, as well as perform background subtraction.

In general we note that the cross dispersion profiles can be quite extended (particularly in the far-UV and in the near-infrared); fluxes derived for extended sources from the `_x2d` files as above assume that the sources are extended on scales which contain the bulk of the cross dispersion flux from a point source. As we make further progress analyzing the cross dispersion profiles and their effect on the accuracies of point source and diffuse source fluxes we will provide updates on the WWW and through the STANs.

See also Chapter 6 of the *STIS Instrument Handbook* for a more detailed discussion of units and conversions for different source types.

23.3.1 Wavelength and Spatial Information

Two-dimensionally extracted spectra have been wavelength calibrated and rectified to a linear wavelength scale. Tasks such as **splot** can work directly on the `_sx2.fits` and `_x2d` files and can read the wavelength header information which is stored in the standard FITS CD-matrix keywords. Alternatively you can use these keywords directly to determine the wavelength or distance along the slit at any pixel as:

$$\lambda(x) = CRVAL1 + (x - CRPIX1) \times CD1_1$$

$$s(y) = (y - CRPIX2) \times CD2_2$$

where $\lambda(x)$ is the wavelength at any given x pixel, and $s(y)$ is the distance along the slit from slit center for any given y pixel, in units of degrees.

23.4 TIME-TAG Data

As described in “Tabular Storage of STIS Data” on page 20-5, raw time-tagged Sdata are stored in an event table which contains separate columns for the x and y pixel coordinates and the arrival time of each detected photon event. There will also be an associated table containing “good time intervals.” In general these data can be analyzed in one of two ways:

- Convert the data to QPOE format and use the tasks in the **xray** and **xtiming** IRAF packages to work with the time series data directly.
- Generate a series of ACCUMulated images from user specified time intervals of data and then process the image(s) with **calstis**.

Using Existing PROS Time Series Analysis Software

The PROS **xray** and the **xtiming** packages in IRAF—originally developed to analyze Roentgen Satellite (ROSAT) data—can be used to do time series analysis of the STIS TIME-TAG data. To use this package, the `*_tag.fits` files need to be converted to PROS QPOE format (extension `*.qp`), using the task **fits2qp**. A few particularly useful tasks within the PROS software package are listed in Table 23.3.

Table 23.3: Useful PROS Tasks

Task	Purpose
period	Find period from a dataset
fldplot	Plot the light curve with the period folded into it
chiplot	Chi-square plot for various periods
ltcurv	Plot simple light curve from a dataset

Note that the times given in the first column of the raw time-tag data (which is the time relative to the start of the exposure) are not corrected for the time delay due to the motion of the earth or the spacecraft. The change in time delay due to the motion of the spacecraft can be a maximum of about 30 millisec in one orbit. The absolute time delay relative to the time-frame at the earth barycenter can itself be much larger. To correct for these effects, the ephemeris of the earth and the spacecraft are necessary. A separate task is being developed at present, similar to the tasks for the High Speed Photometer (HSP), to correct for these effects and to convert the times to the barycenter of the earth. This task can be used by observers, or can be processed at STScI as a special request, for those science uses of TIME-TAG where it becomes an important effect.

Using **inttag** to Produce ACCUM Images of Specified Time Slices

The **inttag** task can be used to integrate STIS TIMETAG data into an image or set of images. The default behavior for **inttag** is to accumulate all events from the table, writing the results as one image set in the output FITS file. The user has the option, however, to specify explicitly a starting time, time interval, and number of intervals over which to integrate, in which case a collection of image sets will be written to the output file, simulating a REPEATOBS ACCUM observation. Breaking the data into multiple, short exposures can be useful not only for variable targets but also to improve the flatfielding when the Doppler shift is significant.

To generate each time-filtered image, **inttag** compares the arrival time for each event to both the user-specified interval and the set of *good time intervals*. (Good time intervals, or *GTIs*, are intervals during which STIS is known to be taking valid data.) If the event qualifies, the raw *x* and *y* coordinates will be mapped to the appropriate output pixel location (to account for binning, subarray location, and Doppler correction for echelle spectroscopy), and the detected photon count of the output pixel will be incremented.

The **inttag** task requires two arguments: the names of the input and output FITS files, in that order. Optional parameters include writing the output image(s) in high-res format (the default is low-res). To specify times interval(s) different from the entire duration of the exposure, specify the starting time in seconds since the beginning of the exposure (*sttime*, the default is INDEF, meaning to start at the beginning of the first GTI), the integration time in seconds (*increment*, the default is INDEF, meaning to end at the last GTI), and the number of intervals (*rcount*, the default is one). If no other value is specified, one ACCUM image set will be created containing all the events. A simple example would be to create a single image set, including only the first 1000 seconds:

```
cl> inttag stis_tag.fits kilo_raw.fits sttime=0 increm=1000
```

A somewhat more complex example is to create 20 high-res imsets, each 100 seconds in duration, starting at the first time in the GTI table. Note that while 20 imsets were specified, fewer may actually be written if any of the 100-second intervals is not contained within any GTI, or if the last time in the GTI table is less than 2000 (i.e. 100 sec * 20 intervals); **inttag** will report how many imsets were created.

```
cl> inttag stis_tag.fits multi_raw.fits sttime=0 \
>>> increm=100 rcount=20 high+
```

Once the images have been created, it is straightforward to process them with **calstis** and analyze the output images or spectra, as appropriate (see “Recalibration of STIS Data” on page 21-29).

23.5 Target Acquisition Data

Target Acquisition Basics

There are two types of STIS target acquisition: ACQ and ACQ/PEAK; for more details on target acquisition, see *STIS ISR 97-03*. For ACQ observations, there are three parts to the target acquisition data that you receive. The first is an image of the target in the target acquisition sub-array (100 x 100 pixels for POINT sources, user-defined for DIFFUSE sources) based on the initial pointing (see Figure 23.1a), `image_raw.fits[sci,1]`. The software then determines the position of the target with a flux-weighted pointing algorithm and calculates the slew needed to place the target at a reference point in the target acquisition sub-array; for DIFFUSE sources, an option to perform a geometric centroiding is available. An image of the target at this corrected position is then obtained (see Figure 23.1b, `image_raw.fits[sci,2]`)—this is the coarse centering. To perform the fine centering (i.e., to place the object precisely in a slit), a 32 x 32 pixel image of the reference 0.2x0.2 aperture is obtained (see Figure 23.1c `image_raw.fits[sci,3]`), and the location of the aperture determined. A fine slew is then performed to center the target in the reference aperture, which should be accurate to 0.5 pixels (0.025 arcseconds). A final slew to center the target in the science aperture is performed at the start of the following science observation.

If a narrow slit is used for the science, an ACQ/PEAK acquisition may have been performed. The slit is scanned across the object with a pattern determined by the aperture selected. The telescope is then slewed to center the star in the aperture, and a confirmation image (a 32 x 32 grid) is obtained; the accuracy of the ACQ/PEAK is 5% of the slit width. Note that the last extension in the file (`image_raw.fits[4]`) contains the values in the individual steps of the ACQ/PEAK (use **listpix** to view these values).

When examining the confirmation image, note that the slit will be illuminated by the sky even if no star is present (see Figure 23.2; `image_raw.fits[sci,1]`). To confirm the presence of a star, use the **imexamine** task and make certain that the FWHM is small. The measured values for the images in Figure 23.2 are given in Table 23.4.

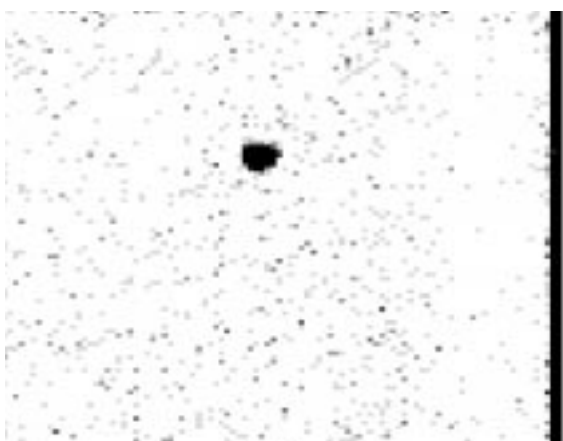
Table 23.4: Measured Brightness for STIS ACQ Image

Type	Enclosed	Gaussian	Direct
Star	1.59	1.57	1.49
Sky	15.22	142.84	4.81

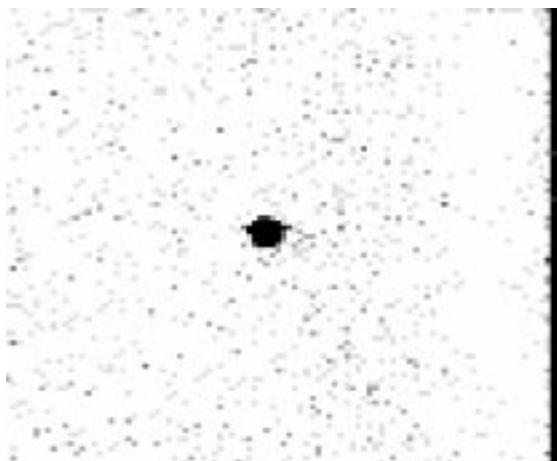
ACQ Data

An examination of the target acquisition data (either from the raw data or the paper products) will allow you to detect gross errors in the centering of your target; note that, if retrieving data via StarView, you must request uncalibrated data to receive target acquisition observations. A comparison of the initial `[sci,1]`

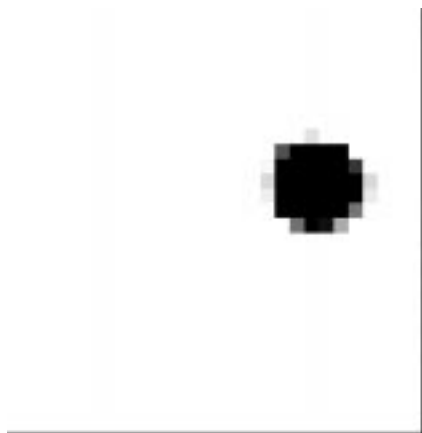
Figure 23.1: Three Stages of an ACQ Observation



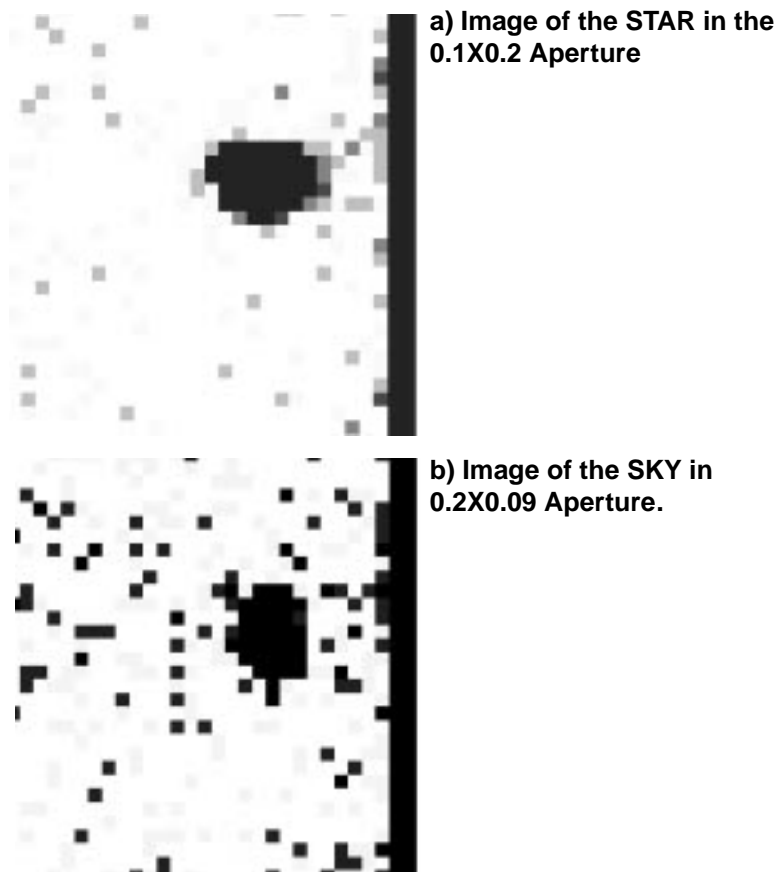
a) Initial Star Position in TA Sub-array



b) Star Position After Coarse Centering



c) Reference Aperture Position (0.2X0.2)

Figure 23.2: ACQ/PEAK Confirmation Images

and post-coarse slew [sci,2] images should show the object moving close to the center of the acquisition sub-array.



Users of STIS data must request "uncalibrated" data when retrieving ACQ and ACQ/PEAK observations through StarView. Since ACQ-like data do not get calibrated there are no calibrated data products.

You can also verify that the fluxes in both images, which are found in the science header under the keyword MAXCHCNT, are consistent by performing the following steps in IRAF :

```
cl> imheader image_raw.fits[1] long+ | grep MAXCHCNT
cl> imheader image_raw.fits[4] long+ | grep MAXCHCNT
```

The first value will be the target flux in the maximum checkbox (3X3 for POINT sources, user-defined for DIFFUSE sources) in the initial image, while the second is the maximum checkbox in the post-coarse slew image. If the fluxes are

not consistent, or if the object did not move closer to the center of the array, there is likely a problem with your acquisition.

ACQ/Peak Data

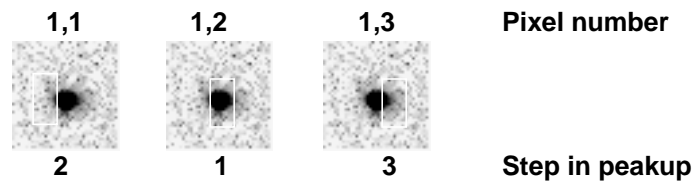
To verify that the ACQ/PEAK worked, examine the flux values at each stage of the pickup (listed in the paper products or in the data file). The fluxes can be found by looking at the fourth extension (`image_raw.fits[4]`) of the pickup data via the IRAF command:

```
cl> listarea image_raw.fits[4]
```

Sample	1	2	3
Line			
1	4707.	260769.	0.

For a 3-step linear pickup, the pixel [1,1] is the leftmost scan position, [2,1] is the middle position, and [3,1] is the rightmost position. See Figure 23.3.

Figure 23.3: Flux Values at Each Stage in Pickup



For a 9-step spiral pattern, pixels [1,1] through [1,3] are the lower row of the pattern, [2,1] through [2,3] are the middle row, and [3,1] through [3,3] are the upper row. Note that one of the steps will always have a value of zero.

To determine the flux in the confirmation image, do the following in IRAF:

```
cl> imstat image_raw.fits[1]fields="image,npix,mean"
```

This will give you an output like the following:

```
cl> imstat o4de01jdq_raw.fits[1]

#           IMAGE      NPIX    MEAN
o4de01jdq_raw.fits[1]  32704   8.241
```

The total counts in the image is the product of the number of pixels (NPIX) and the mean value (MEAN), or 269,514 in this example.

Note that you will need to perform one correction to the mean value prior to your comparison. The flux values in the pickup scan have been adjusted to subtract the minimum flux value in the pickup data (which is why one value in the pickup is always zero). This value needs to be subtracted from the counts in the confirmation to do a proper comparison. The value can be found in pixel 712 of the `_spt` image; to display the value on the screen, do the following in IRAF:

```
cl> listpix image_spt.fits[1] | grep 712
```

In the example, the value was 6008, which means the corrected number of counts in the confirmation image is 263,506.

Comparison of the maximum flux value during the pickup (260,769) with the flux in the post-ACQ/PEAK confirmation image (263,506) should show that the flux in the confirmation image was greater than or equal to the maximum flux in the pickup grid. If this is not the case, then there is likely a problem with your pickup acquisition.