

FOS Data Analysis

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Several IRAF/STSDAS routines exist for displaying and analyzing spectroscopic data (see Table 3.5). General purpose spectroscopic tasks, such as **splot**, **mkmultispec**, and others, are also described in Chapter 3.

This chapter presents a series of generally unrelated discussions of individual data analysis topics several of which were inspired by frequently asked questions received by the STScI FOS team from General Observers. Also included are descriptions of additional useful IRAF/STSDAS tasks for evaluating, improving, and analyzing FOS data.

33.1 Calculating Exposure Times

The basic times most observers will be interested in are:

- Start and end times (of the observation, or of the integration for a given group).

- Exposure time per pixel (i.e., the integration time which contributes to the counts in each pixel), for the whole observation, or a given group.

The following section presents detailed information on the determination of these quantities from header information *only*. The determination of FOS start and stop times from header information is limited to an accuracy of +0.125 to -0.255 seconds (see Chapter 32). If you need more accurate start times, contact the Help Desk, help@stsci.edu. In Table 33.1, we summarize how to obtain these basic quantities from header keywords and group parameters.

Table 33.1: Timing Information for FOS

Type of Information	Source	Units
Observation start time	EXPSTART ^a	Modified Julian date
Group start time	FPKTTIME ^b – group_elapsed_time	Modified Julian date
Group_elapsed_time	FPKTTIME (group 1) – EXPSTART	Seconds
Group exposure time <i>per pixel</i>	EXPOSURE ^b	Seconds
Group end time	FPKTTIME ^b	Modified Julian date
Observation end time	FPKTTIME ^b (last group)	Modified Julian date

a. Header keyword

b. Group parameter

33.1.1 Exposure Time Details

The different times in the FOS headers are:

- **LIVETIME:** The fundamental unit of integration time. This is the time between opening and closing the 512 accumulators. The shortest time is 3 ms. The header keyword is LIVETIME.
- **DEADTIME:** Time required for housekeeping chores. It is normally 10ms. The header keyword is DEADTIME.
- **Exposure time per pixel:** This is the integration time per pixel that contributes to the counts observed in that pixel. This differs from the exposure time per spectrum because of substepping. The header keyword EXPOSURE gives the total exposure time for a non-edge pixel in seconds.
- **Exposure time per group:** This is the integration time for a given group, which is equivalent to the integration time per diode and is exclusive of instrument overheads. The exposure time of the group (exp_{group}) (units of seconds) using the header keywords is determined as follows:

$$exp_{group} = EXPOSURE \times NXSTEPS$$

This simple equation in terms of the basic FOS time and data acquisition terms is given to the full accuracy of the FOS clock by:

$$exp_{group} = \text{LIVETIME} \times 7.8125\text{E-}6 \times \text{XINTS} \times \text{NXSTEPS} \times \text{OVERSCAN} \times \text{YSTEPS} \times \text{NPAT}$$

In this calculation we have not accounted for the deadtime because we are interested in calculating only the time over which the photons were collected.

- **Elapsed time per group:** This is the total time associated with an entire group. It is longer than the exposure time of a group because of the added deadtime. The following equation can be used to determine the elapsed time of a group for nearly all observations.

$$elapsed\ time_{group} = (\text{LIVETIME} + \text{DEADTIME}) \times 7.8125\text{E-}6 \times \text{INTS} \times \text{NXSTEPS} \times \text{OVERSCAN} \times \text{YSTEPS} \times \text{SLICES} \times \text{NPAT}$$

This elapsed time can be used to determine the approximate start and stop time of each group in the data. The procedure is as follows:

The FPKTTIME in the group parameters of the .d0h file is the time at which the FOS memory for that group was read out and *is inclusive of all deadtime for the group*. Unfortunately, it may also include an indeterminate additional interval of up to 0.13 second caused by HST SDF overheads. In the headers this time is given (to the accuracy of about 0.125 second) in units of modified Julian date, which is the Julian date minus 2400000.5. This time can be converted from modified Julian date to the standard notation using the **epoch** task. For many FOS datasets in the HST Archive obtained prior to January 1, 1995, the exposure start time is incorrectly populated. The time at which the integration was started is given by:

$$start\ time = \text{FPKTTIME}_{group} - elapsed\ time_{group}$$



Please note that the start time for each individual group should be calculated from the FPKTTIME of the relevant group and not simply by a recursive addition of group elapsed time to the start time of a previous group.



The group parameters can be determined by running the task **grlist** to determine all the groups in the d0h file and then finding the value of the necessary keyword using **hedit**. Note that the FPKTTIME is accurate only to approximately 1/8 second.

- **Exposure time for the observation:** This is the total time during which the FOS accumulated data for the observation and is given in the header keyword EXPTIME. This should be the exposure time given in Phase II instructions. This is given by the equation:

$$exp_{total} = EXPOSURE \times NXSTEPS \times NREADS \times NMCLEARs$$

In the basic FOS data acquisition units, this is:

$$exp_{total} = LIVETIME \times 7.8125E-6 \times INTS \times NXSTEPS \times OVERSCAN \times YSTEPS \times NPAT \times SLICES \times NREAD \times NMCLEARs$$

- **Elapsed time for the observation:** This is the total time spent by the FOS for a given observation, which includes the deadtime during which photons were not accumulated. Corresponding to the exposure time for the observation is the elapsed time for the observation. This is given by:

$$elapsed\ time_{observation} = (LIVETIME + DEADTIME) \times 7.8125E-6 \times INTS \times NXSTEPS \times OVERSCAN \times YSTEPS \times NPAT \times SLICES \times NREAD \times NMCLEARs$$

33.1.2 Timing



Observation start and stop times are determined from the header information with a precision of +0.125 to -0.255 second, while exposure times are determined with a precision of 7.8125 microseconds. This has particular impact on certain RAPID mode timings as described in “RAPID Mode Observation Timing Uncertainties” on page 33-5.

Start and End Times

The *start* time of the observation (i.e., the time at which the integration was begun for the first group of data) is given in modified Julian date in the header keyword EXPSTART. The modified Julian date is the Julian date minus 2400000.5. Prior to January 1, 1995 EXPSTART was incorrectly populated with FPKTTIME. You should insure that your EXPSTART is approximately equal to the difference between FPKTTIME for the first group and group elapsed time.

The *end* time of the integration for each group of data is given in modified Julian days in the group parameter FPKTTIME. The end time of an observation is the FPKTTIME of the last group of the observation. Again, in many FOS datasets obtained before January 1, 1995, the EXPEND keyword is incorrectly populated with LPKTTIME rather than FPKTTIME of the last observation group. You should insure that the FPKTTIME of the last group has been used for EXPEND.

To calculate the approximate group start time, subtract the *group elapsed time* from FPKTTIME. The group elapsed time (which will be nearly the same for all groups in a given observation) can be calculated in two ways: 1) for datasets obtained after January 1, 1995: as FPKTTIME for the first group of data minus EXPSTART, or 2) for any dataset: from the formula given in the previous section. The start time of each subsequent group is then given as FPKTTIME for that group minus the group elapsed time (see Table 33.1).

As noted earlier, an additional uncertainty of approximately 0.13 seconds exists since the HST Science Data Formatter can be delayed in issuing the command to read out the FOS memory, which is recorded as FPKTTIME.

Exposure Times

The *elapsed time* for an observation differs from the *exposure time* (the actual integration time during which counts are accumulated) because the elapsed time includes the deadtime during which the FOS is doing housekeeping (e.g., reading out the diodes) and therefore not integrating. The total *exposure time* for the entire observation (all groups) is given by the keyword EXPTIME in the data header.

The *exposure time per pixel*, the integration time which contributed to the flux observed in a given pixel, differs from the exposure time for the spectrum whenever substepping is employed. The exposure time is divided among the NXSTEPS individual substepped spectra which together produce the single spectrum. The (typical) exposure time per pixel is therefore given by the exposure time divided by NXSTEPS. This quantity is contained in the group parameter EXPOSURE.¹

33.2 RAPID Mode Observation Timing Uncertainties

Under certain circumstances, the start times of individual exposures in an FOS RAPID mode time series must be calculated by a special algorithm, which requires information available only from the engineering telemetry stream. The reason for this requirement is that the interval between individual groups in a RAPID (or rarely, ACCUM) mode sequence is not always constant

If *absolute* or *relative* start times of RAPID mode exposure sequences must be known to accuracies more precise than 0.125 seconds, then we recommend that RAPID mode observers contact the Help Desk (E-mail: help@stsci.edu) for help in determining the precise start times of the exposures.

FOS ISR 154 provides a detailed description of the causes of uncertainties in the start times of FOS exposures and provides many low-level details of FOS data taking

1. Note, however, that the actual exposure time for a given pixel may be different from EXPOSURE, either because the pixel did not receive input from OVERSCAN diodes (because it was an edge pixel or because it was fed by input from one or more disabled diodes), or because a particular readout was rejected by the onboard burst noise rejection algorithm. Thus EXPOSURE actually reports the maximum possible exposure time per pixel. The **calfos** task correctly calculates the *count rate* of each pixel, taking into account the number of diode readouts which contributed to the counts observed in each pixel, using the information in the disabled diode reference table to compensate for disabled diodes and the noise rejections tallied in the reject array (the .d1h file) to compensate for times when the counts from a particular diode were not accumulated into memory due to noise rejection.

33.3 Heliocentric Radial Velocity Calculation

FOS output wavelengths (.c0 files) are placed on the wavelength system of the dispersion coefficients in the CCS6 reference table. As described in Chapter 31 those coefficients contain an “internal/external” correction to account for the different illumination patterns produced on the dispersers by internal and external beams. However, no corrections for spacecraft motions of any kind are applied to **calfos**-calibrated wavelengths.

The procedure described here calculates the heliocentric motion of the Earth at the time of observation. This procedure does *not* correct for the small effect (at FOS dispersions) of HST orbital motion.

The IRAF task **rvcorrect** is used to compute radial velocity corrections. **rvcorrect** is in the IRAF **astutil** package and it calls on task **observatory**, which is also found in **astutil**. The following steps are an example of its use for an HST dataset where the HST velocity around the Earth is ignored (maximum residual: +/- ~7.8 km/s):

1. Set parameters to their default values.

```
cl> unlearn rvcorrect
```

Use the default **observatory** task parameters except the following, which must be set to prevent **rvcorrect** from calculating an unwanted diurnal velocity correction based on the observatory position with respect to the Earth's center.

Figure 33.1: Observatory pset Values

```

as> lpar observatory
  command = "list"          Command (set|list|images)
  obsid = "obspars"        Observatory to set, list, or image default
  images =                  List of images
  override =                Observatory identification
  (verbose = no)           Verbose output?\n
  (observatory = "obspars") Observatory identification
  (name = " ")             Observatory name
  (longitude = 0.)         Observatory longitude (degrees)
  (latitude = 0.)         Observatory latitude (degrees)
  (altitude = -6378204.8)  Observatory altitude (meters)
  (timezone = 0.)         Observatory time zone

```

2. Create an ASCII file (named **rvcor.in** in the following example) with a row entry for each spectrum. Each row will contain: UT, RA, DEC, EPOCH, and Observed Velocity (more examples are provided in the help file for the task). Here is an example of file **rvcor.in**:

```

93 01 21 18:50:07 0.2974443291667E+03 0.4896100000000E+02 2000 0
93 01 21 20:05:09 0.2974443291667E+03 0.4896100000000E+02 2000 0

```

3. Run the **rvcorrect** task:

```
cl>rvcorrect f=rvcor.in > outputfile
```

The above example produced the following output file. VHELIO contains the (very small, in this case) correction for the heliocentric velocity of the telescope with respect to the target.

HJD	VOBS	VHELIO	VLSR	VDIURNAL	VLUNAR	VANNUAL	VSOLAR
2449009.81098	0.00	2.38	2.72	0.000	0.001	2.381	0.342
2449009.88335	0.00	2.35	2.69	0.000	0.001	2.349	0.342

Read the **rvcorrect** task help carefully, particularly to insure that you keep the signs of the velocities in the appropriate frame.

33.4 FOS/BL G160L Zero-Order Photometric Calibration

A rough calibration of the FOS/BL G160L zero-order sensitivity for photometry is provided here. No zero-order calibrations for other dispersers are available.

The FOS/BL G160L zero-order was normally read out by the diode array. The spectral passband for the zero-order of this detector and disperser combination ranged from 1150 to approximately 5500 Å. For a flat continuum source, the effective wavelength of the passband was approximately 2400 Å. The signal strength in the zero-order depended on the integral of the target spectral energy distribution and the detector sensitivity over the entire bandpass.

A very approximate calibration of the FOS/BL zero-order sensitivity was originally provided in *FOS ISR 091* and improved in Eracleous and Horne, *ApJ*, 433, 313, 1994. These original calibrations are updated here for some errors and are superseded by the sensitivity values, S , given below.

$$\text{Flux (FOS/BL G160 zero-order) [in mJ]} = C / (T \times S)$$

where C is the detected counts per second in the entire profile of the zero-order spectral feature, T is aperture throughput relative to the 4.3 aperture as unity (see Table 32.5 and Table 32.6), and $S = 520$ (pre-COSTAR) or 620 (post-COSTAR) counts per second per mJ.



Note that since C is defined as the total signal in the zero-order feature, *but is somewhat peculiarly expressed in counts/sec*, you must be careful about the distinction between total exposure time and exposure per pixel in the output .c5h data products. Therefore, you should calculate C by adding up the zero-order signal in your .c5h file and dividing by NXSTEPS.

This calibration is based upon pre-COSTAR observations of AE Aqr and A0620-00, both of which are close binary systems with quite red spectra that are dominated at wavelengths longer than 3000 Å by their K-type components. This approximate calibration is estimated to be accurate to about 50%.

33.5 Converting FOS X,Y to Spacecraft V2,V3

Although the conversion of telescope offsets from the FOS (x,y) reference frame to the telescope (V2,V3) reference frame is provided in the FOS paper products for all acquisition slews, you may occasionally need to calculate this rotation for other purposes. As noted in Chapter 29, the FOS (x,y) coordinate system is defined so that the x-axis is parallel to the diode array and the y-axis is perpendicular to the diode array. Further, the (x,y) coordinate frame is rotated with respect to the telescope (V2,V3) coordinate frame. Figures 33.2 and 33.3 show the coordinate axes for both detectors before COSTAR was installed. The (V2,V3) axes were rotated 180° by the introduction of COSTAR.

Figure 33.2: Pre-COSTAR Orientation of FOS/BL, (Here PA_APER=110°)

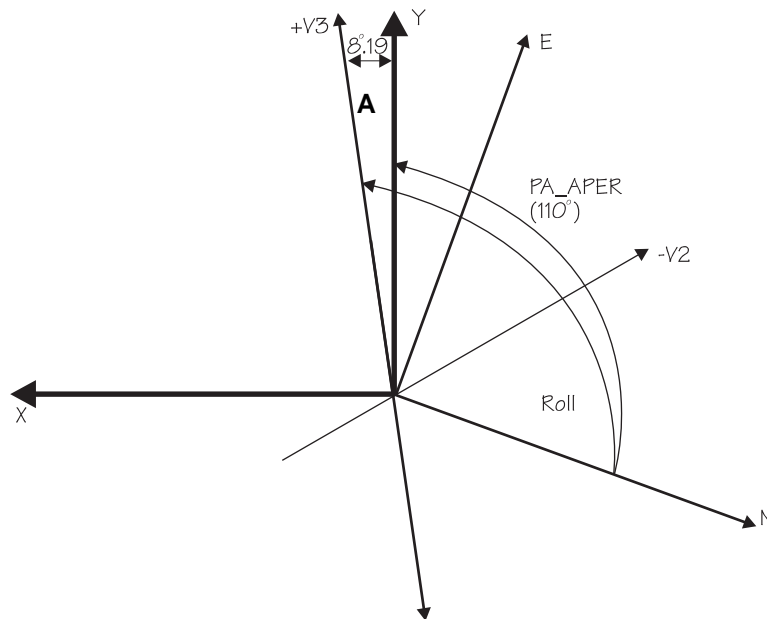
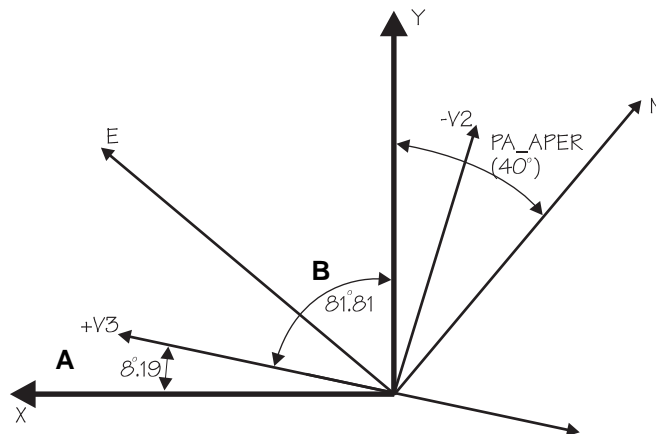


Figure 33.3: Pre-COSTAR Orientation of FOS/RD (PA_APER=40°)



From the figures above we see that the coordinate transformation for FOS/BL is given by:

$$V2 = X \sin(A) - Y \cos(A)$$

$$V3 = X \cos(A) + Y \sin(A)$$

While the pre-COSTAR transformation for FOS/RD is given by:

$$V2 = X \sin(B) - Y \cos(B)$$

$$V3 = X \cos(B) + Y \sin(B)$$

where:

- pre-COSTAR: $A = 8.19^\circ$ and $B = 81.81^\circ$
- post-COSTAR: $A = 188.19^\circ$ and $B = 261.81^\circ$

33.5.1 Converting X,Y to RA, Dec

The conversion of an (x,y) offset to an (RA,Dec) offset is, of course, an additional simple rotation added to the expressions in section “Converting FOS X,Y to Spacecraft V2,V3” on page 33-8. The position angle of the aperture (PA_APER) is the angular orientation of the +y-axis of the aperture measured in degrees east of North. PA_APER is given in the FOS paper products and in science data headers.

33.6 Other Useful FOS Tasks in STSDAS

Chapter 3 provides details on several IRAF/STSDAS tasks useful for displaying and analyzing spectroscopic data; these tasks include **splot**, **mkmultispec**, **fwplot**, and **sgraph**. Following are brief descriptions of several more tasks that are useful for investigating or improving FOS data quality. In all cases, the on-line IRAF/STSDAS help file contains additional practical information.

33.6.1 deaccum

This task unbundles individual groups of an ACCUM multigroup spectrum. In ACCUM operation the data are readout at regular intervals and the output after each readout is stored as a separate group containing the accumulated sum of all readouts. The product of the **deaccum** task is a multigroup spectrum in which each individual group contains only the signal accumulated during each individual readout interval. This data format is very useful when the groups are plotted together for inspecting the effects of noisy diodes or poor guiding during the exposure. This check is always a good idea to do as it allows inspection of the entire spectrum as opposed to the more limited paper product group count diagnostic.

We recommend running **deaccum** with all of your ACCUM mode .c1h files. It will also work with statistical error (.c2h) files and correctly unbundles these data in quadrature. This task will *not* work for data files that contain wavelengths (.c0h) or data quality values (.q0h or .cqh files). The group parameter EXPOSURE is updated in the output image headers to reflect the change in exposure time associated with each data group. For example, to unstack the calibrated flux data in the image y3ci0203t.c1h, and write the results to the new image y3ci0203u.c1h, use the command:

```
f0> deaccum y3ci0203t.c1h y3ci0203u.c1h
```

33.6.2 gimpcor

The size of geomagnetically-induced motion can often be important when analyzing photometric losses due to image drift off the diode array and when assessing the widths or wavelengths of spectral features.

Since the **calfos** (pre-onboard) GIM correction is applied on an integral pixel basis in the x -direction only, uncorrected motions of up to +/- 0.5 pixels can occur in X . This effect is much smaller for observations corrected by the onboard GIM correction. For observations obtained prior to the implementation of the onboard GIM correction (the presence of header keyword YFGIMPEN set to “T” tells you if the onboard correction has been performed), the actual decimal magnitude of GIM motion can be evaluated with STSDAS task **gimpcor**. This information can be useful for evaluation of the GIM-related uncertainties in observing modes to which the correction is not applied, as well, such as pre-onboard GIM-correction spectropolarimetry and IMAGE mode.

This task calculates the x -direction GIM correction in fractional diodes predicted by the FOS GIM model. Rounding of the output to the nearest integer gives the actual correction that would have been applied by **calfos** in normal pipeline processing if the OFF_CORR switch were enabled.

The size of the y -motion, which is important for the evaluation of photometric losses, is also calculated. Recall that no GIM correction is made in the y -direction prior to the implementation of the onboard GIM correction.

gimpcor is essentially a small version of **calfos**, but **gimpcor** does not actually perform any corrections. All inputs required for running **calfos** are also required for running **gimpcor**. The image motion corrections are output in diodes, not pixels, for x and Y -base units for y . For example, the following command can be used to show the magnitude of the GIM correction for the observation y0nt0303t (an observation made in RAPID mode, with each line corresponding to each readout of the science diodes). Note that components of the geomagnetic field are also given along the V1, V2, and V3 axes.

```
fo> gimpcor y0nt0303t
Y0NT0303T      XOFF      YOFF      B(V1)      B(V2)      B(V3)
Y0NT0303T      0.7937     -18.9236   -0.144756  -0.252337  -0.187240
Y0NT0303T      0.7774     -22.6758   -0.158107  -0.241623  -0.200176
Y0NT0303T      0.7540     -26.3918   -0.171826  -0.228918  -0.211748
Y0NT0303T      0.7235     -29.9800   -0.185674  -0.214425  -0.221575
      .....
Y0NT0303T      -0.1363     30.6008   -0.142325  -0.105515   0.195814
Y0NT0303T      -0.0940     31.9168   -0.134098  -0.119314   0.193947
```

33.6.3 unwrap

The FOS accumulators will overflow if more than 65,535 counts are recorded in any individual readout interval. In many cases an overflow can be corrected by the **unwrap** task. All pixels greater than a threshold value will be examined for wraparound. This algorithm is not foolproof, especially if more than one wraparound has occurred. Some experimentation with the threshold value usually results in a good correction for reasonably smooth continua or emission lines. An alternate IDL algorithm that is somewhat more robust than **unwrap** is available on the FOS WWW page in the Calibration Tools section.

This example will unwrap the image `y20vk10gr.d0h` using a threshold value of 20000 and creating an unwrapped image called `uw10g.d0h`.

```
fo> unwrap y20vk10gr.d0h uw10g.d0h thresh=20000.
```

33.6.4 waveoffset

Determination of wavelength offsets between two spectra can be made with the STSDAS routine **waveoffset**.

This routine computes the offset of one spectrum from a reference spectrum, as a function of wavelength and diode position in the frame of the reference spectrum. The input spectra may be divided into a number of equally sized bins. Each bin in the target spectrum is cross-correlated with the corresponding bin in the reference spectrum and an offset is determined. The offsets for all bins are placed in an output table as both diode and wavelength offsets.

The following example will compute the offset between upper and lower apertures for the spectra in file `h57red`. The upper aperture is in the first group of the file and the lower aperture in the second group. The wavelengths for the first group are stored in `wh57red` (group 1). Results are written to a table called `offsets.tab`.

```
fo> waveoffset h57red[1] wh57red[1] h57red[2] tab=offsets
```


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The basic times most observers will be interested in are:

- Start and end times (of the observation, or of the integration for a given group).

- Exposure time per pixel (i.e., the integration time which contributes to the counts in each pixel), for the whole observation, or a given group.

The following section presents detailed information on the determination of these quantities from header information *only*. The determination of FOS start and stop times from header information is limited to an accuracy of +0.125 to −0.255 seconds (see Chapter 32). If you need more accurate start times, contact the Help Desk, help@stsci.edu. In Table 33.1, we summarize how to obtain these basic quantities from header keywords and group parameters.

Table 33.1: Timing Information for FOS

Type of Information	Source	Units
Observation start time	EXPSTART ^a	Modified Julian date
Group start time	FPKTTIME ^b – group_elapsed_time	Modified Julian date
Group_elapsed_time	FPKTTIME (group 1) – EXPSTART	Seconds
Group exposure time <i>per pixel</i>	EXPOSURE ^b	Seconds
Group end time	FPKTTIME ^b	Modified Julian date
Observation end time	FPKTTIME ^b (last group)	Modified Julian date

a. Header keyword

b. Group parameter

33.1.1 Exposure Time Details

The different times in the FOS headers are:

- **LIVETIME:** The fundamental unit of integration time. This is the time between opening and closing the 512 accumulators. The shortest time is 3 ms. The header keyword is LIVETIME.
- **DEADTIME:** Time required for housekeeping chores. It is normally 10ms. The header keyword is DEADTIME.
- **Exposure time per pixel:** This is the integration time per pixel that contributes to the counts observed in that pixel. This differs from the exposure time per spectrum because of substepping. The header keyword EXPOSURE gives the total exposure time for a non-edge pixel in seconds.
- **Exposure time per group:** This is the integration time for a given group, which is equivalent to the integration time per diode and is exclusive of instrument overheads. The exposure time of the group (exp_{group}) (units of seconds) using the header keywords is determined as follows:

$$exp_{group} = EXPOSURE \times NXSTEPS$$

This simple equation in terms of the basic FOS time and data acquisition terms is given to the full accuracy of the FOS clock by:

$$exp_{group} = LIVETIME \times 7.8125E-6 \times INTS \times NXSTEPS \times OVERSCAN \times YSTEPS \times NPAT$$

In this calculation we have not accounted for the deadtime because we are interested in calculating only the time over which the photons were collected.

- **Elapsed time per group:** This is the total time associated with an entire group. It is longer than the exposure time of a group because of the added deadtime. The following equation can be used to determine the elapsed time of a group for nearly all observations.

$$elapsed\ time_{group} = (LIVETIME + DEADTIME) \times 7.8125E-6 \times INTS \times NXSTEPS \times OVERSCAN \times YSTEPS \times SLICES \times NPAT$$

This elapsed time can be used to determine the approximate start and stop time of each group in the data. The procedure is as follows:

The FPKTTIME in the group parameters of the .d0h file is the time at which the FOS memory for that group was read out and *is inclusive of all deadtime for the group*. Unfortunately, it may also include an indeterminate additional interval of up to 0.13 second caused by HST SDF overheads. In the headers this time is given (to the accuracy of about 0.125 second) in units of modified Julian date, which is the Julian date minus 2400000.5. This time can be converted from modified Julian date to the standard notation using the **epoch** task. For many FOS datasets in the HST Archive obtained prior to January 1, 1995, the exposure start time is incorrectly populated. The time at which the integration was started is given by:

$$start\ time = FPKTTIME_{group} - elapsed\ time_{group}$$



Please note that the start time for each individual group should be calculated from the FPKTTIME of the relevant group and not simply by a recursive addition of group elapsed time to the start time of a previous group.



The group parameters can be determined by running the task **grlist** to determine all the groups in the d0h file and then finding the value of the necessary keyword using **hedit**. Note that the FPKTTIME is accurate only to approximately 1/8 second.

- **Exposure time for the observation:** This is the total time during which the FOS accumulated data for the observation and is given in the header keyword EXPTIME. This should be the exposure time given in Phase II instructions. This is given by the equation:

$$exp_{total} = EXPOSURE \times NXSTEPS \times NREADS \times NMCLEARs$$

In the basic FOS data acquisition units, this is:

$$exp_{total} = LIVETIME \times 7.8125E-6 \times INTS \times NXSTEPS \times OVERSCAN \times YSTEPS \times NPAT \times SLICES \times NREAD \times NMCLEARs$$

- **Elapsed time for the observation:** This is the total time spent by the FOS for a given observation, which includes the deadtime during which photons were not accumulated. Corresponding to the exposure time for the observation is the elapsed time for the observation. This is given by:

$$elapsed\ time_{observation} = (LIVETIME + DEADTIME) \times 7.8125E-6 \times INTS \times NXSTEPS \times OVERSCAN \times YSTEPS \times NPAT \times SLICES \times NREAD \times NMCLEARs$$

33.1.2 Timing



Observation start and stop times are determined from the header information with a precision of +0.125 to -0.255 second, while exposure times are determined with a precision of 7.8125 microseconds. This has particular impact on certain RAPID mode timings as described in “RAPID Mode Observation Timing Uncertainties” on page 33-5.

Start and End Times

The *start* time of the observation (i.e., the time at which the integration was begun for the first group of data) is given in modified Julian date in the header keyword EXPSTART. The modified Julian date is the Julian date minus 2400000.5. Prior to January 1, 1995 EXPSTART was incorrectly populated with FPKTTIME. You should insure that your EXPSTART is approximately equal to the difference between FPKTTIME for the first group and group elapsed time.

The *end* time of the integration for each group of data is given in modified Julian days in the group parameter FPKTTIME. The end time of an observation is the FPKTTIME of the last group of the observation. Again, in many FOS datasets obtained before January 1, 1995, the EXPEND keyword is incorrectly populated with LPKTTIME rather than FPKTTIME of the last observation group. You should insure that the FPKTTIME of the last group has been used for EXPEND.

To calculate the approximate group start time, subtract the *group elapsed time* from FPKTTIME. The group elapsed time (which will be nearly the same for all groups in a given observation) can be calculated in two ways: 1) for datasets obtained after January 1, 1995: as FPKTTIME for the first group of data minus EXPSTART, or 2) for any dataset: from the formula given in the previous section. The start time of each subsequent group is then given as FPKTTIME for that group minus the group elapsed time (see Table 33.1).

As noted earlier, an additional uncertainty of approximately 0.13 seconds exists since the HST Science Data Formatter can be delayed in issuing the command to read out the FOS memory, which is recorded as FPKTTIME.

Exposure Times

The *elapsed time* for an observation differs from the *exposure time* (the actual integration time during which counts are accumulated) because the elapsed time includes the deadtime during which the FOS is doing housekeeping (e.g., reading out the diodes) and therefore not integrating. The total *exposure time* for the entire observation (all groups) is given by the keyword EXPTIME in the data header.

The *exposure time per pixel*, the integration time which contributed to the flux observed in a given pixel, differs from the exposure time for the spectrum whenever substepping is employed. The exposure time is divided among the NXSTEPS individual substepped spectra which together produce the single spectrum. The (typical) exposure time per pixel is therefore given by the exposure time divided by NXSTEPS. This quantity is contained in the group parameter EXPOSURE.¹

33.2 RAPID Mode Observation Timing Uncertainties

Under certain circumstances, the start times of individual exposures in an FOS RAPID mode time series must be calculated by a special algorithm, which requires information available only from the engineering telemetry stream. The reason for this requirement is that the interval between individual groups in a RAPID (or rarely, ACCUM) mode sequence is not always constant

If *absolute* or *relative* start times of RAPID mode exposure sequences must be known to accuracies more precise than 0.125 seconds, then we recommend that RAPID mode observers contact the Help Desk (E-mail: help@stsci.edu) for help in determining the precise start times of the exposures.

FOS ISR 154 provides a detailed description of the causes of uncertainties in the start times of FOS exposures and provides many low-level details of FOS data taking

1. Note, however, that the actual exposure time for a given pixel may be different from EXPOSURE, either because the pixel did not receive input from OVERSCAN diodes (because it was an edge pixel or because it was fed by input from one or more disabled diodes), or because a particular readout was rejected by the onboard burst noise rejection algorithm. Thus EXPOSURE actually reports the maximum possible exposure time per pixel. The **calfos** task correctly calculates the *count rate* of each pixel, taking into account the number of diode readouts which contributed to the counts observed in each pixel, using the information in the disabled diode reference table to compensate for disabled diodes and the noise rejections tallied in the reject array (the .d1h file) to compensate for times when the counts from a particular diode were not accumulated into memory due to noise rejection.

33.3 Heliocentric Radial Velocity Calculation

FOS output wavelengths (.c0 files) are placed on the wavelength system of the dispersion coefficients in the CCS6 reference table. As described in Chapter 31 those coefficients contain an “internal/external” correction to account for the different illumination patterns produced on the dispersers by internal and external beams. However, no corrections for spacecraft motions of any kind are applied to **calfos**-calibrated wavelengths.

The procedure described here calculates the heliocentric motion of the Earth at the time of observation. This procedure does *not* correct for the small effect (at FOS dispersions) of HST orbital motion.

The IRAF task **rvcorrect** is used to compute radial velocity corrections. **rvcorrect** is in the IRAF **astutil** package and it calls on task **observatory**, which is also found in **astutil**. The following steps are an example of its use for an HST dataset where the HST velocity around the Earth is ignored (maximum residual: +/- ~7.8 km/s):

1. Set parameters to their default values.

```
cl> unlearn rvcorrect
```

Use the default **observatory** task parameters except the following, which must be set to prevent **rvcorrect** from calculating an unwanted diurnal velocity correction based on the observatory position with respect to the Earth's center.

Figure 33.1: Observatory pset Values

```

as> lpar observatory
  command = "list"          Command (set|list|images)
  obsid = "obspars"        Observatory to set, list, or image default
  images =                  List of images
  override =                Observatory identification
  (verbose = no)           Verbose output?\n
  (observatory = "obspars") Observatory identification
  (name = " ")             Observatory name
  (longitude = 0.)         Observatory longitude (degrees)
  (latitude = 0.)         Observatory latitude (degrees)
  (altitude = -6378204.8)  Observatory altitude (meters)
  (timezone = 0.)         Observatory time zone
  
```

2. Create an ASCII file (named **rvcor.in** in the following example) with a row entry for each spectrum. Each row will contain: UT, RA, DEC, EPOCH, and Observed Velocity (more examples are provided in the help file for the task). Here is an example of file **rvcor.in**:

```

93 01 21 18:50:07 0.2974443291667E+03 0.4896100000000E+02 2000 0
93 01 21 20:05:09 0.2974443291667E+03 0.4896100000000E+02 2000 0
  
```

3. Run the **rvcorrect** task:

```
cl>rvcorrect f=rvcor.in > outputfile
```

The above example produced the following output file. VHELIO contains the (very small, in this case) correction for the heliocentric velocity of the telescope with respect to the target.

HJD	VOBS	VHELIO	VLSR	VDIURNAL	VLUNAR	VANNUAL	VSOLAR
2449009.81098	0.00	2.38	2.72	0.000	0.001	2.381	0.342
2449009.88335	0.00	2.35	2.69	0.000	0.001	2.349	0.342

Read the **rvcorrect** task help carefully, particularly to insure that you keep the signs of the velocities in the appropriate frame.

33.4 FOS/BL G160L Zero-Order Photometric Calibration

A rough calibration of the FOS/BL G160L zero-order sensitivity for photometry is provided here. No zero-order calibrations for other dispersers are available.

The FOS/BL G160L zero-order was normally read out by the diode array. The spectral passband for the zero-order of this detector and disperser combination ranged from 1150 to approximately 5500 Å. For a flat continuum source, the effective wavelength of the passband was approximately 2400 Å. The signal strength in the zero-order depended on the integral of the target spectral energy distribution and the detector sensitivity over the entire bandpass.

A very approximate calibration of the FOS/BL zero-order sensitivity was originally provided in *FOS ISR* 091 and improved in Eracleous and Horne, *ApJ*, 433, 313, 1994. These original calibrations are updated here for some errors and are superseded by the sensitivity values, S , given below.

$$\text{Flux (FOS/BL G160 zero-order) [in mJ]} = C / (T \times S)$$

where C is the detected counts per second in the entire profile of the zero-order spectral feature, T is aperture throughput relative to the 4.3 aperture as unity (see Table 32.5 and Table 32.6), and $S = 520$ (pre-COSTAR) or 620 (post-COSTAR) counts per second per mJ.



Note that since C is defined as the total signal in the zero-order feature, *but is somewhat peculiarly expressed in counts/sec*, you must be careful about the distinction between total exposure time and exposure per pixel in the output .c5h data products. Therefore, you should calculate C by adding up the zero-order signal in your .c5h file and dividing by NXSTEPS.

This calibration is based upon pre-COSTAR observations of AE Aqr and A0620-00, both of which are close binary systems with quite red spectra that are dominated at wavelengths longer than 3000 Å by their K-type components. This approximate calibration is estimated to be accurate to about 50%.

33.5 Converting FOS X,Y to Spacecraft V2,V3

Although the conversion of telescope offsets from the FOS (x,y) reference frame to the telescope ($V2,V3$) reference frame is provided in the FOS paper products for all acquisition slews, you may occasionally need to calculate this rotation for other purposes. As noted in Chapter 29, the FOS (x,y) coordinate system is defined so that the x -axis is parallel to the diode array and the y -axis is perpendicular to the diode array. Further, the (x,y) coordinate frame is rotated with respect to the telescope ($V2,V3$) coordinate frame. Figures 33.2 and 33.3 show the coordinate axes for both detectors before COSTAR was installed. The ($V2,V3$) axes were rotated 180° by the introduction of COSTAR.

Figure 33.2: Pre-COSTAR Orientation of FOS/BL, (Here PA_APER= 110°)

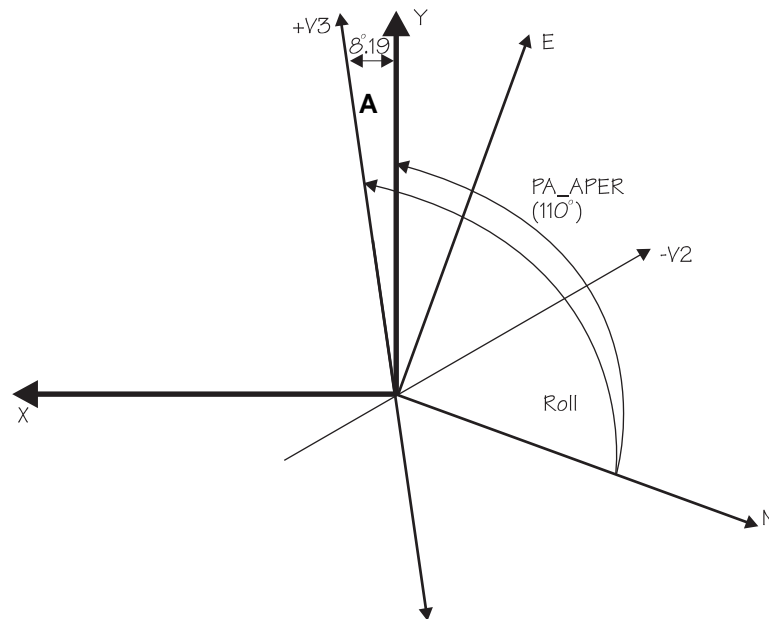
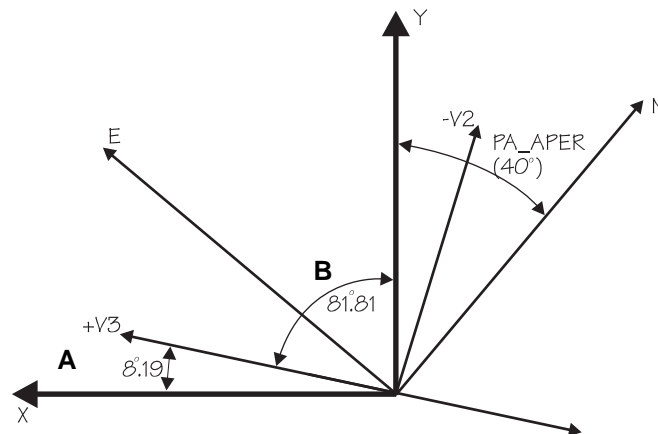


Figure 33.3: Pre-COSTAR Orientation of FOS/RD (PA_APER= 40°)



From the figures above we see that the coordinate transformation for FOS/BL is given by:

$$V2 = X \sin(A) - Y \cos(A)$$

$$V3 = X \cos(A) + Y \sin(A)$$

While the pre-COSTAR transformation for FOS/RD is given by:

$$V2 = X \sin(B) - Y \cos(B)$$

$$V3 = X \cos(B) + Y \sin(B)$$

where:

- pre-COSTAR: $A = 8.19^\circ$ and $B = 81.81^\circ$
- post-COSTAR: $A = 188.19^\circ$ and $B = 261.81^\circ$

33.5.1 Converting X,Y to RA, Dec

The conversion of an (x,y) offset to an (RA,Dec) offset is, of course, an additional simple rotation added to the expressions in section “Converting FOS X,Y to Spacecraft V2,V3” on page 33-8. The position angle of the aperture (PA_APER) is the angular orientation of the +y-axis of the aperture measured in degrees east of North. PA_APER is given in the FOS paper products and in science data headers.

33.6 Other Useful FOS Tasks in STSDAS

Chapter 3 provides details on several IRAF/STSDAS tasks useful for displaying and analyzing spectroscopic data; these tasks include **splot**, **mkmultispec**, **fwplot**, and **sgraph**. Following are brief descriptions of several more tasks that are useful for investigating or improving FOS data quality. In all cases, the on-line IRAF/STSDAS help file contains additional practical information.

33.6.1 deaccum

This task unbundles individual groups of an ACCUM multigroup spectrum. In ACCUM operation the data are readout at regular intervals and the output after each readout is stored as a separate group containing the accumulated sum of all readouts. The product of the **deaccum** task is a multigroup spectrum in which each individual group contains only the signal accumulated during each individual readout interval. This data format is very useful when the groups are plotted together for inspecting the effects of noisy diodes or poor guiding during the exposure. This check is always a good idea to do as it allows inspection of the entire spectrum as opposed to the more limited paper product group count diagnostic.

We recommend running **deaccum** with all of your ACCUM mode .c1h files. It will also work with statistical error (.c2h) files and correctly unbundles these data in quadrature. This task will *not* work for data files that contain wavelengths (.c0h) or data quality values (.q0h or .cqh files). The group parameter EXPOSURE is updated in the output image headers to reflect the change in exposure time associated with each data group. For example, to unstack the calibrated flux data in the image y3ci0203t.c1h, and write the results to the new image y3ci0203u.c1h, use the command:

```
f0> deaccum y3ci0203t.c1h y3ci0203u.c1h
```

33.6.2 gimpcor

The size of geomagnetically-induced motion can often be important when analyzing photometric losses due to image drift off the diode array and when assessing the widths or wavelengths of spectral features.

Since the **calfos** (pre-onboard) GIM correction is applied on an integral pixel basis in the x -direction only, uncorrected motions of up to +/- 0.5 pixels can occur in X . This effect is much smaller for observations corrected by the onboard GIM correction. For observations obtained prior to the implementation of the onboard GIM correction (the presence of header keyword YFGIMPEN set to “T” tells you if the onboard correction has been performed), the actual decimal magnitude of GIM motion can be evaluated with STSDAS task **gimpcor**. This information can be useful for evaluation of the GIM-related uncertainties in observing modes to which the correction is not applied, as well, such as pre-onboard GIM-correction spectropolarimetry and IMAGE mode.

This task calculates the x -direction GIM correction in fractional diodes predicted by the FOS GIM model. Rounding of the output to the nearest integer gives the actual correction that would have been applied by **calfos** in normal pipeline processing if the OFF_CORR switch were enabled.

The size of the y -motion, which is important for the evaluation of photometric losses, is also calculated. Recall that no GIM correction is made in the y -direction prior to the implementation of the onboard GIM correction.

gimpcor is essentially a small version of **calfos**, but **gimpcor** does not actually perform any corrections. All inputs required for running **calfos** are also required for running **gimpcor**. The image motion corrections are output in diodes, not pixels, for x and Y -base units for y . For example, the following command can be used to show the magnitude of the GIM correction for the observation y0nt0303t (an observation made in RAPID mode, with each line corresponding to each readout of the science diodes). Note that components of the geomagnetic field are also given along the V1, V2, and V3 axes.

```
fo> gimpcor y0nt0303t
Y0NT0303T      XOFF      YOFF      B(V1)      B(V2)      B(V3)
Y0NT0303T      0.7937     -18.9236   -0.144756  -0.252337  -0.187240
Y0NT0303T      0.7774     -22.6758   -0.158107  -0.241623  -0.200176
Y0NT0303T      0.7540     -26.3918   -0.171826  -0.228918  -0.211748
Y0NT0303T      0.7235     -29.9800   -0.185674  -0.214425  -0.221575
      .....
Y0NT0303T      -0.1363     30.6008   -0.142325  -0.105515   0.195814
Y0NT0303T      -0.0940     31.9168   -0.134098  -0.119314   0.193947
```

33.6.3 unwrap

The FOS accumulators will overflow if more than 65,535 counts are recorded in any individual readout interval. In many cases an overflow can be corrected by the **unwrap** task. All pixels greater than a threshold value will be examined for wraparound. This algorithm is not foolproof, especially if more than one wraparound has occurred. Some experimentation with the threshold value usually results in a good correction for reasonably smooth continua or emission lines. An alternate IDL algorithm that is somewhat more robust than **unwrap** is available on the FOS WWW page in the Calibration Tools section.

This example will unwrap the image `y20vk10gr.d0h` using a threshold value of 20000 and creating an unwrapped image called `uw10g.d0h`.

```
fo> unwrap y20vk10gr.d0h uw10g.d0h thresh=20000.
```

33.6.4 waveoffset

Determination of wavelength offsets between two spectra can be made with the STSDAS routine **waveoffset**.

This routine computes the offset of one spectrum from a reference spectrum, as a function of wavelength and diode position in the frame of the reference spectrum. The input spectra may be divided into a number of equally sized bins. Each bin in the target spectrum is cross-correlated with the corresponding bin in the reference spectrum and an offset is determined. The offsets for all bins are placed in an output table as both diode and wavelength offsets.

The following example will compute the offset between upper and lower apertures for the spectra in file `h57red`. The upper aperture is in the first group of the file and the lower aperture in the second group. The wavelengths for the first group are stored in `wh57red` (group 1). Results are written to a table called `offsets.tab`.

```
fo> waveoffset h57red[1] wh57red[1] h57red[2] tab=offsets
```

