

## Orbital drift of the EIS wavelength scale

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**UPDATE (18-Aug-2021):** The method described by Kamio et al. (2010) no longer works correctly and should not be used for data obtained from 2018 onwards. Generally you can recognise that the method is not working if you see vertical bands in the Doppler maps with amplitudes of around  $10 \text{ km s}^{-1}$ . The best solution is to fit the emission line of interest and then identify a band of quiet Sun. By averaging the line centroid over this band you will see the orbital variation, which can then be subtracted. The text below is retained from the previous version of the document (1.1).

## 1 Overview

If a Gaussian is fit to an emission line profile over an entire raster, then plotting the resulting image of the centroid variation shows a strong oscillation in the X-direction. An example is shown in Fig. 1, where the alternating bands of red and blue correspond to red and blue shifts of the emission line. The period of the oscillation is 98 mins and corresponds to the orbital period of the spacecraft, thus the oscillation is clearly due to thermal effects related to the satellite’s orbit around the Earth. In this document we refer to this effect as “spectrum drift” and we describe methods of correcting it.

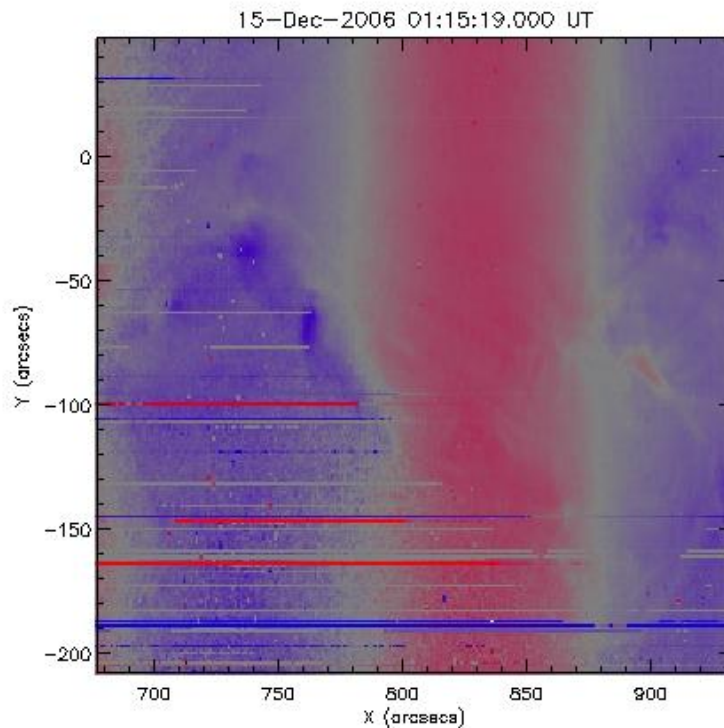


Figure 1: A velocity map derived from an EIS raster. EIS rasters from right-to-left, and the vertical bands of blue and red correspond to the spectrum drift during the raster.

## 2 What causes the oscillation?

The Hinode spacecraft is oriented such that it always points at the Sun, and it does not rotate relative to the Sun. This means that each side of the spacecraft receives a variable illumination from the Earth as the spacecraft orbits the Earth. For EIS this means that in some parts of the orbit the instrument is directly illuminated by the Earth, and in other parts it is shadow behind SOT.

The movement of the emission lines on the CCD is thus understood as being due to an oscillation in the angle of the reflecting surface of the EIS grating. The changing temperature of the instrument in the vicinity of the grating leads to a small rotation of the grating position. The effect corresponds to a  $\pm 1.5$  pixel amplitude oscillation in the positions of the lines on the detector. The EIS pixels have a size of  $13.5 \mu\text{m}$  and the grating-detector separation is 1.44 m thus the tilt in the grating position is only  $0.0008^\circ$ . However, Fig. 1 shows that this tiny movement dominates the Doppler shifts due to real motions on the Sun.

## 3 Properties of the spectrum drift

The paper of Kamio et al. (2010) gives a thorough discussion of the spectrum drift. Some key points are given below.

- The amplitude of the oscillation is about 1.5 pixels and is the same for all wavelengths. This means, however, that in velocity space the amplitude varies with wavelength, being around  $50 \text{ km s}^{-1}$  for Fe XII  $\lambda 195.12$  and  $35 \text{ km s}^{-1}$  for Fe XV  $\lambda 284.16$ .
- During the eclipse season (April–August) the oscillation significantly deviates from a sinusoidal pattern.
- Over a day the line centroids oscillate about a center which itself drifts with time. This drift is seasonal in nature and due to the varying separation of the Sun and the Earth.

## 4 Correcting for the spectrum drift

Initial efforts at correcting the spectrum drift involved using the science data themselves. Typically the strongest line in the spectrum, Fe XII  $\lambda 195.12$ , was fit at each pixel in a raster, and the centroid averaged in the Y-direction. This average centroid yielded the spectrum drift during the course of the raster which could then be used to correct other lines. The method assumes there are no large scale flows within the raster that would distort the spectrum drift. A common variation for active region data is to identify a quiet part of the raster and then only average over this region so that any flows within the active region do not affect the determination of the spectrum drift.

Since the EIS instrument contains 31 temperature sensors that yield values with a 10 s cadence, then an alternative method of determining the spectrum drift is to correlate the temperature sensor readings with the spectrum line positions through a model. This work was performed by Kamio et al. (2010) and, since around 2010 September, this new method is now the default way of correcting

for the spectrum drift. Since the temperature sensor data form part of the EIS housekeeping data stream, then the method is referred to as the “HK method”.

Full details on how the model works are provided by Kamio et al. (2010), and we give a brief summary below:

- The model is based on measurements of the centroid of Fe XII  $\lambda 195.12$  line over the entire course of the Hinode mission.
- As new data are obtained, the model correction is continually updated.
- The model sets the average  $\lambda 195.12$  velocity over the whole mission to be  $0 \text{ km s}^{-1}$ , thus the spectrum drift correction also yields a form of absolute wavelength calibration.
- Following the spectrum drift correction, centroids should be accurate to  $4.4 \text{ km s}^{-1}$ .
- The data needed for performing the spectrum drift correction are stored in the EIS Solarsoft distribution.

## 5 How is the spectrum drift correction implemented?

An empirical model has been developed to reproduce the drift of the EIS spectrum using instrumental house keeping temperatures and the relative motion of the spacecraft, see Kamio et al. (2010).

The wavelength correction can be found using `eis_wave_corr_hk.pro`, the `gethkwavecorr()` method of the `eis_data` object or `eis_prep.pro`. All procedures use specially prepared house keeping data files that are distributed with SolarSoft in the directory `$EIS_DATA/wave_corr`. If the house keeping files that are needed for correcting a certain EIS raster are missing in your SolarSoft installation, the new routines will search for the files in `$EIS_WAVE_CORR_HK_DATA` (if this environment variable is set), and in the current working directory. If the files are not found, they will automatically be downloaded from the Oslo archive and saved in `$EIS_WAVE_CORR_HK_DATA` (if set) or to the current working directory (if not set).

The following three examples demonstrate different methods to obtain the new wavelength correction. The example data-set is specified through

```
IDL> paths = '~/hinodedata/eis/mission/2007/12/11/eis_10_20071211_162413.fits.gz'
```

(please modify the path to the location where your Hinode data are stored).

### 5.1 `eis_getwindata.pro`

This routine reads a specified wavelength window into an IDL structure. By default it also calls the routine `eis_wave_corr.pro` and stores the wavelength correction related to the spectrum drift within the structure, in a tag called `wave_corr_t`. For example:

```
IDL> wd=eis_getwindata(paths,195.12)
IDL> help,wd.wave_corr_t
<Expression>    DOUBLE    = Array[256]
```

This array gives the wavelength correction for each exposure in the raster required to put the emission line on the absolute wavelength calibration scale of the Kamio et al. (2010) method.

The windata structure has an additional tag called `wave_corr` that combines the spectrum drift with the EIS slit tilt (see EIS Software Note #4) to give a 2D array.

The `wave_corr` array stored in the windata structure is used by the Gaussian fitting routine `eis_auto_fit.pro` to perform the spectrum drift and slit tilt corrections, so that the velocity map that results from the fit is free from these instrumental effects.

## 5.2 `eis_wave_corr.pro`

The `eis_wave_corr` routine was modified in 2010 September so that it uses the HK method by default. Previously it has used moments of the Fe XII  $\lambda$ 195.12 line to determine the spectrum drift. The calling sequence is:

```
IDL> eis_wave_corr, paths, wvl_corr, dw_tilt, dw_t
```

(the last two parameters are optional). To use the previous method to determine `wvl_corr`, set the `/OLD` keyword.

There is a routine called `eis_wave_corr_hk` which returns `wvl_corr`, `dw_tilt` and `dw_t` in the identical manner to `eis_wave_corr` (in fact it is called by `eis_wave_corr`) but which has the additional two keywords:

**wvl\_cube:** If set to a named variable, `wvl_cube` will return a 3 dimensional wavelength cube in the format used by `mk_analysis.pro` of the Component Fitting System for IDL (`cfitsio`) package.

**lam:** the underlying methods of `eis_data` calculate the wavelength correction in pixels, and we assume that the shift in pixels is the same for all lines formed at any location on the two detectors. However, when measured in Angstroms the line centre variation and the slit tilt will vary slightly with wavelength. As default, `eis_wave_corr_hk` assumes that the corrections are to be calculated for the Fe XII 195 Å line, but the `lam` keyword may be set to the wavelength of the line you want to investigate. For example, the following code compares the spectrum drift for the Fe XII  $\lambda$ 195.12 and Fe XV  $\lambda$ 284.16 lines.

```
IDL> eis_wave_corr_hk, paths, wvl_corr_hk, dw_tilt_hk, dw_t_hk
IDL> plot, dw_t_hk, /xst, /yst
IDL> eis_wave_corr_hk, paths, wvl_corr_hk2, dw_tilt_hk2, dw_t_hk2,
      wvl_cube=wvl_cube, lam=284.16
IDL> help, wvl_cube
IDL> loadct,12 & oplot, dw_t_hk2, color=170
```

Finally, `eis_wave_corr_hk` can take a level 0 or level 1 `eis_data` object reference as input instead of a file name:

```
IDL> o = obj_new('eis_data',paths)
IDL> eis_wave_corr_hk, o, wvl_corr
```

### 5.3 gethkwavecorr(), a new eis\_data method

When creating an eis\_data object, the aux\_data will contain two new null pointers, hkpixcorrtilt and hkpixcorrtime:

```
IDL> o = obj_new('eis_data',paths)
IDL> help, o->getaux_data(),/str
```

The two pointers will become valid when the method gethkwavecorr() is called (i.e. when you try to access the contents of the pointers):

```
IDL> corr = o->gethkwavecorr()
IDL> help, corr,/str
IDL> help, o->getaux_data(),/str
```

The gethkwavecorr() may be called with a wavelength as input parameter, or with the keyword wvl\_cube set, to get the same functionality as for the eis\_wave\_corr\_hk wrapper as explained above.

```
IDL> corr = o->gethkwavecorr(/wvl_cube)
IDL> help,corr,/str
IDL> corr = o->gethkwavecorr(284.16)
IDL> oplot,corr.time,color=0
```

### 5.4 eis\_prep.pro, with hkwavecorr set

eis\_prep.pro now accepts the keyword hkwavecorr. If set, the resulting level 1 file will contain the wavelength correction information.

```
IDL> eis_prep,paths,outdir='~/',/hkwavecorr,/default,/quiet,/save
IDL> o = obj_new('eis_data','~/eis_l1_20071211_162413.fits')
IDL> help,o->getaux_data(),/str
IDL> corr = o->gethkwavecorr()
IDL> oplot,corr.time
```

## References

Kamio, S., Hara, H., Watanabe, T., Fredvik, T. & Hansteen, V. H., 2010, Sol. Phys., 266, 209