8. CDS CALIBRATION

"Exit, pursued by a flare" - from The Winter's Tale,
"found" by E. Tandberg-Hanssen & A. Gordon Emslie, with apologies to W. Shakespeare (1564-1616).

8.1 Introduction

The CDS scientific program has as its goal the measurement of accurate spectral line intensities, both relatively and absolutely, in order to apply established techniques to derive diagnostic information on the plasmas of the solar atmosphere. Absolute intensities and intensity ratios can be used to obtain information on abundances, density and temperature. Such information can be obtained only with an accurate knowledge of the instrument sensitivity and performance.

Since past experience has shown that EUV optics degrade in time, the pre-launch intensity calibration of CDS must be supported by a calibration and monitoring scheme during the mission. However, intensity calibration is only one aspect of the calibration of CDS. It is clear that, to obtain the best possible results from CDS, we must fully understand the performance of the instrument across various parameter ranges, and we must be able to compare this performance with other instruments on the SOHO platform, especially SUMER. Thus, we have considered several techniques for calibration and alignment. These include:

- An absolute intensity calibration (intensity in energy flux units vs wavelength),
- A relative intensity calibration (intensity in instrument counts vs wavelength),
- A multi-instrument cross-calibration (intensies of CDS vs SUMER, EIT, UVCS)
- A wavelength calibration (wavelength vs pixel),
- A pixel calibration (pixel relative sensitivity - i.e. detector flat fielding),
- An absolute alignment (alignment & equation of pointing vs solar co-ordinates),
- A relative alignment (CDS alignment vs other instrument alignments),
- A telescope calibration (measurement of point spread function).

Each of these will be discussed in the following sections, where a scientific justification is given. Calibration and alignment activities took place prior to launch but the instrument performance will also be monitored throughout the mission. The policy on this for each of the above listed items is given in the following sections.

8.2 Absolute and Relative Intensity Calibration

The intensity we measure for a particular spectral line will be in counts per second. It is important to be able to convert this to photon $cm^{-2}.s^{-1}.ster^{-1}$ to a reasonable accuracy. Absolute intensity measurements are required to generate accurate emission measure studies, to investigate the amount of material along the line of sight as a function of temperature, and to investigate absolute abundances. Such results are essential for modelling the solar atmosphere. A good absolute calibration provides the basis for a good relative calibration since the sensitivity will not be uniform across the wavelength range.

Much could be done with intensity ratios even in the absence of an absolute intensity calibration. Density and temperature diagnostics can be extracted and have been explored for the CDS wavelength range, though these will be limited to lines near to one another in wavelength. Similarly, relative abundance estimates can be made. However, it is clear that the full potential of these techniques can only be tapped with a good absolute calibration.

8.2.1 Pre-Launch Calibration

It was concluded during the early development of CDS that the only viable procedure for pre-flight intensity calibration was by comparison to synchrotron light from an electron storage ring, by the use of a transfer source. Such an exercise was funded through ETH in Zurich and was performed by a collaboration involving the Physikalisch Technische Bundesanstalt (PTB) in Berlin, and RAL.

For each calibration activity, the transfer source was calibrated against the BESSY electron storage ring, in Berlin, and transported to the RAL. There, the source was used to illuminate the CDS instrument to achieve an end to end calibration. Then, the source was returned to Berlin for post-calibration checks.

The transfer source is a high-current hollow cathode discharge lamp which emits intense unpolarized line radiation from a buffer gas (He, Ne, Ar, Kr) and the cathode material (99.5% aluminium) at wavelengths longer than 130 Å. Equipped with a compact two stage differential pumping system, the hollow cathode source allows windowless observation of its radiation under ultrahigh-vacuum conditions. The source has been optimised to operate as a radiometric standard of radiant intensity. A detailed description of its operation and radiometric characterisation is given by Hollandt *et al.* (1993).

For the sensitivity calibration of CDS twenty-five emission lines from the calibration source were selected, which cover the full spectral range of the instrument. The photon flux of these emission lines has been determined by comparison with the spectral photon flux of the electron storage ring BESSY. The storage ring is a primary radiometric standard source since the spectral photon flux of the synchrotron radiation can be calculated from the knowledge of the storage ring parameters (Riehle et al., 1985, Arnold et al., 1994).

The photon flux in a range of EUV emission lines of the calibration source beam has been established to be in the range 10^4 to 10^8 photons/s and is comparable to the accepted solar flux of CDS. The relative uncertainty of the measurement of the source photon flux is between 6% and 8% (1 sigma confidence level). The specific calibration source emission lines, their associated uncertainty and the contributions to that uncertainty are given by Harrison et al. (1995).

This aspect of the calibration is an attempt to measure the efficiency product $\varepsilon_t \varepsilon_m \varepsilon_g \varepsilon_d$, where ε_t, ε_m, ε_g, ε_d (see section 3) are efficiencies of the telescope, scan mirror, grating and detector, respectively. This will not only be a function of wavelength but also a function of angles of incidence, governed by such things as the scan mirror position and the source off-set angle with respect to the telescope axis. Thus, the efficiency product cannot be thoroughly represented by a simple plot against wavelength. A full discussion is presented in a separate report (in preparation).

However, as a sample of the results obtained, for observations made on-axis, with the scan mirror in its central position, the efficiency product for the GIS detectors was found to lie in the range 1-2.5 x 10^{-4} for the first two detectors, 2-5.5 x 10^{-4} for the third, and 1 x 10^{-4} for the longest wavelength detector. Given pre-build estimates of telescope, scan mirror, grating and detector efficiencies of about 0.25, 0.80, 0.03 and 0.1, we predicted an efficiency product of order 6 x 10^{-4}, recognising that this figure was rather optimistic. Thus, the measured to predicted intensity ratio appears to be of order 20-90%, depending on wavelength, which is an encouraging result.

8.2.2 Calibration During Flight

There are a variety of calibration options during the flight. These are detailed below:

(i) Cross-calibration with rocket flights

The CDS team is closely linked to the team operating the SERTS EUV rocket. It has been decided that the SERTS flight of spring 1996, and possibly one a year later, may be used as cross-calibration flights. A significant wavelength overlap between the SERTS instrument and the GIS/NIS will be used, probably in the region 310-360 Å. The SERTS payload will be calibrated at RAL using the PTB source in exactly the same way as CDS.

(ii) Calibration from the SOHO full-Sun EUV monitor (SEM)

A stable UV full-Sun monitor is included on the SOHO spacecraft, as part of the CELIAS package. This device is proposed to cover the 170-700Å region with a narrow band across the 304Å region. This would, in theory, allow us to identify absolute changes with time, though the data will be for full-Sun, requiring significant projection or full Sun rasters for useful comparisons to CDS. We would not expect to produce a calibration for CDS against the monitor to better than 20-30%.

(iii) CDS monitoring of contamination

CDS does contain two Quartz Crystal Monitors, the voltages from which may be used to assess to some extent the degree of contamination within the optical bench during flight.

(iv) CDS monitoring of quiet Sun intensities

Past EUV solar observations have not demonstrated that the quiet Sun provides stable intensities, say to within several tens of percent. However, this variation may be due to calibration difficulties and problems in target definitions rather than actual quiet Sun variations. For example, published quiet Sun intensities in $erg.cm^{-2}.s^{-1}.ster^{-1}$ for Mg X 609.79Å are given at 245, 125, 281, 147 and 197. Similarly, for Ne VIII 770.41Å we find 97, 54, 111 and 55. Some of these were projected from full-Sun intensities, some were from short rocket flight data. We must examine quiet Sun targets early in the mission to demonstrate that quiet Sun monitoring is a useful option. However, with a precise target definition, it would be surprising if it is not. Full GI and NI spectra should be made of quiet targets about once per week to monitor the slow degradation of the optics across the entire wavelength range.

Of course, with a constant view of the Sun over many years, SOHO will be able to provide the best standard solar spectra in the EUV, thus making way for such comparisons in the future. This can only be valuable with a good absolute calibration in the pre-launch phase.

(v) CDS monitoring of invariant line ratios

We will also calibrate by the use of invariant line ratios. Consider two spectral lines which arise from transitions from the same level, *n*, to differing levels, *l* and *m*. If the population of the upper level is N_n and the transition probability between *n* and level *x* is given by A_{nx}, we have intensities for the two lines as

$$I(\lambda_m) = N_n A_{nm} \nu_{nm}, \qquad \text{and} \qquad I(\lambda_l) = N_n A_{nl} h \nu_{nl},$$

where h is Planck's constant and ν is the frequency of the transition. The signal we actually record, $S(\lambda)$, as counts at the detector depends on an efficiency factor $\varepsilon(\lambda)$, which can be expressed in the following way, $S(\lambda_x) = \varepsilon(\lambda_x) I(\lambda_x)/(h\nu_{nx})$.Thus the ratio of the efficiencies of the instrument at the two wavelengths is given by

$$\varepsilon(\lambda_m)/\varepsilon(\lambda_l) = \{S(\lambda_m) / S(\lambda_l)\} \{A_{nl} / A_{nm}\}.$$

The second component of the right hand side is known and the measured intensities are known, thus we can obtain a relative calibration at the two wavelengths. By using a series of such line pairs we may provide a relative calibration over a wide wavelength range.

This method, first discussed by Griffin and McWhirter (1962), has been the subject of several studies across the UV/EUV region, and one may expect to perform a relative calibration, using this technique, across the CDS wavelength range and between the SOHO EUV/UV spectroscopic instruments.

Klose and Wiese (1989) have listed such branching ratios from H, He, Li and Be like ions in a wavelength range which includes the 150−1600Å band appropriate to the SOHO coronal instruments. They list some 200 ratios. Such ratios confined to the CDS wavelength bands have been examined.

An acknowledged problem with branching ratios is that they are invariably weak - indeed, examining established solar EUV line lists, we cannot identify useful branching ratios in the CDS wavelength range. It appears that the branching ratio method is of little use unless further ratios can be found or new lines identified using CDS. The latter is quite likely.

One result of the weakness of the branching ratio technique has been a search for other invariant ratios. Neupert and Kastner (1983) have suggested that certain line pairs are invariant to the conditions seen in the solar atmosphere and their line lists do include lines bright enough to be seen by CDS. This has to be treated with some caution since so much depends on the accuracy of atomic data which cancels in the branching ratio method. We are investigating this method thoroughly for CDS at this time.

Note that the variations of photometric response across CDS will not be a steep function of wavelength. Therefore, comparisons of intensities from nearby lines will be ideal for ratio work.

(vi) Cross-calibration of the CDS NIS and GIS detectors

Cross-calibration between the CDS spectrometers is possible through the use of common wavelength bands. These are:

- First Order: 308-338 Å
- First/Second Order: 328-381 Å (NIS 1st, GIS 2nd order)

CDS will make appropriate, regular scans in these wavelength ranges.

(vii) Cross-calibration between CDS and other SOHO instruments

This is described in the next section.

8.3 Multi-Instrument Cross-Calibration

We note that SUMER has performed a similar pre-flight intensity calibration to CDS, using a hollow cathode lamp calibrated against the BESSY synchrotron. Another feature of the CDS and SUMER experiments is the deliberate wavelength overlap to allow for cross calibration mentioned above.

Cross-calibration between CDS and SUMER is possible through the use of common wavelength bands. These regions are:

- 656–785Å GIS 1st order, SUMER 2nd order
- 513–633Å NIS 1st order, SUMER 2nd order

We must ensure that appropriate overlying fields of view are recorded in these wavelength bands on regular occasions.

8.4 Wavelength Calibration

Although the prime aim for CDS is to measure line intensities, we also require a good wavelength calibration, i.e. the wavelength vs pixel characteristics. Given spectral resolving powers of up to 10^4, we should aim at an absolute knowledge of the wavelength position to <1 pixel.

The known wavelengths of the emission lines from the ionised gas in the radiation output from the hollow cathode source provided a convenient wavelength calibration for the CDS instrument. For this calibration a narrow entrance slit - the 2x240 arcsec slit for the NI system and the 2x2 arcsec slit for the GI system - was used to give the highest spectral resolution.

The GIS data are recorded as one-dimensional arrays - 2048 for each detector. The positions of a number of lines were determined, on each detector, by fitting Gaussian profiles to the data. The relationship between these positions and their corresponding wavelengths was determined by a least-squares straight-line fit. Hence the observed wavelength ranges were determined as shown in Table 1.2.

For the NIS VDS detector, windows on the CCD were selected which either contained the whole spectral range for each detector (NI1 or NI2) or, in some cases, two or three smaller windows around the lines of interest. The full spectral range covered nominally 1024 pixels per detector and the spatial window recorded was usually 140 pixels. The dispersion and ranges were then found as for the GIS detectors. The resulting wavelength ranges are also given in Table 1.2.

The CDS calibrated wavelength ranges are within a few Å of the target ranges and thus, all emission lines of prime interest to the CDS experiment are covered.

During the flight, one would wish to check wavelength locations by the accurate determination of line positions. However, this must be done with velocity shifts removed. To first order, we may build up a calibration standard by calculating the average locations of all lines in the CDS detectors during the mission. We have the advantage of viewing a long slit in normal incidence. Since the entire slit will rarely show consistent motion along its whole length, we may examine the relative velocities along the slit.

Finally, since SUMER will be performing a calibration using chromospheric lines, and we have overlapping wavelengths, we can cross-calibrate. This will occur in the ranges mentioned above. Such a direct cross-calibration will cater for the longer wavelength NI detector and the longest wavelength GI detector. Second order lines in these ranges can be used to calibrate the first NI band and the second GI band.

8.5 Telescope Calibration

The spatial resolution of the telescope is effectively defined by the full width at half maximum intensity (FWHM) of the point spread function, that is the FWHM of the intensity distribution resulting from the observation of an infinitely distant point source. This was measured in the following way. A hollow cathode light source filled with helium (radiation principally at the wavelengths 304 and 584 Å) was placed behind a pinhole of size 5 µm, 125 m from the telescope. At the telescope focus, measurements were made with a 2-D intensified CCD detector, consisting of an open microchannel plate stack within, through the photoelectric effect, in-coming photons produce electron showers which, on arrival at a phosphor coating, are converted to visible light which is directed through a fibre optic to a CCD. Utilising a transputer driven centroiding algorithm the system is able to resolve down to the pore size of the microchannel plate (i.e. about 10 µm).

Figure 8.1 shows the profiles of the point spread function. Four traces are shown; for each of the NIS and GIS apertures of the telescope the point spread function is given in the direction of wavelength dispersion (X) and the direction perpendicular to it (Y). The FWHM values are 1.2 and 1.7 arcseconds, for the GIS aperture, in the X and Y directions, respectively. Similarly, for the NIS aperture, the values are 1.2 and 1.5 arcseconds. The half energy width in all cases is less than 5 arcseconds.

Figure 8.1 The telescope point spread function: For the GIS and NIS apertures curves are given for the direction of wavelength dispersion (X) (dash-dot and dotted curves, respectively) and the direction perpendicular to it (Y) (dashed and solid, respectively).

In addition, a measure of the large angle scatter of the point spread function gives an indication of the potential for intensity contamination from sources not in the line of sight. Figure 8.2 illustrates the large angle scatter performance of the telscope. The plot is produced from observations made at 68 Å and is normalised to unity to demonstrate the contribution at any point due to a source of intensity unity located at the core. The shape of the curve at distances from the core of less than 20 arcseconds is heavily influenced by the detector pixel size and should be ignored. However, values of order $10^{-4.3}$, $10^{-5.4}$, $10^{-6.2}$, $10^{-6.6}$, $10^{-7.8}$ and $10^{-8.5}$ are indicated for distances of 20, 50, 100, 150, 500 and 1000 arcseconds from the core (the last two values are not shown in Figure 8.2). Technical limitations resulted in no equivalent measurements at wavelengths more suited to the CDS range. However, in moving to longer wavelengths, the scatter is expected to be lower, by a factor of up to 5.

Figure 8.2 The telescope large angle scatter at 68 Å for the region up to 200 arcseconds from the point spread function core.

Although the point spread function was measured in the laboratory, it would be nice to confirm the telescope performance during flight. In theory, this can be done by viewing point-like stellar sources. Since CDS is limited to pointing within 1° of Sun centre, we are normally limited to studying the intensity of stars which come within 1° of the Sun. This could be supplemented by re-pointing SOHO, though this is an option we do not consider to be open to us.

A study of potential stellar sources is underway and some discussion has taken place. Current belief is that the potential sources are too weak for a realistic observation. In addition, a stellar source will travel at 0.04 arcsec/sec requiring active repointing for durations of over 50 seconds (which are inevitable).

8.6 Pixel Calibration

The sensitivity across a detector may vary, due to pixel sensitivities or masking within the optical path of the instrument. Thus, we need to compare the performance of each location of the detectors by flat fielding, i.e. an even illumination across the detector with a monochromatic EUV source. Some flat-field observations have been performed in the laboratory, but schemes to monitor these in flight are being considered.

Since the gratings and detectors do not move with respect to one another, the line structure is fixed on the detector microchannel plates. This will cause degradation of the plates in the vicinity of the lines with time. This requires a continual monitoring scheme. Monitoring the intensity of the line centre with the line wings and nearby lines should be sufficient to identify the degradation and to allow correction. Once again, this kind of exercise requires regular full spectra to be returned from both spectrometers.

8.7 Pointing and Alignment

CDS will not have a full-Sun field of view. We will select scientific targets and repoint. Our requirement is to see features at the few arc second level. This demands a pointing stability of 2 arc seconds over, say, tens of minutes, but says nothing of the pointing accuracy.

The accuracy to which we point at any target must be a function of the accuracy of our knowledge of the control of the CDS pointing with respect to SOHO and the pointing of SOHO itself. It is essential that CDS can be pointed to anywhere on the solar disc and to a reasonable portion of the solar corona. Pointing was discussed in chapter 1. However, the Sun's diameter is 0.5^o, and the present plan is to allow CDS to point to any location within a square of sides 0.85^o, centred on Sun centre, with the corners overlying solar north, south, east and west. The pointing mechanism will provide a step size of 1 arcsec.

We assume that SOHO is directed to Sun centre. There is a potential offset between the SOHO boresight and any individual experiment of up to 4.5 arc minutes. This means that it is possible for two instruments to be offset with respect to one another by 9 arc minutes ($0.3R_{sun}$). The full range of CDS ensures that any CDS/SUMER misalignment can be covered by re-pointing CDS.

The spacecraft pointing requirements and performance are given in the minutes of the Third SWT meeting at ESTEC (Nov. 1989) as:

Table 8.3 Pointing and Alignment Parameters

Absolute Pointing Accuracy	10 arcsec
Relative Pointing Accuracy	1 arcsec in 15 min
Absolute Roll Accuracy	15 arcmin
Relative Roll Accuracy	1.5 arcmin in 15 min
FPSS Initial Calibr. Accuracy	5 arcsec
Attitude Control Error	1 arcmin
Potential Experiment Misalignment (in flight)	4.5 arcmin
Potential Misalignment Drift	12 arcsec per year

[FPSS - Fine Pointing Sun Sensor]

As far as CDS is concerned, the pointing accuracy ought to be limited to half of the width of the smallest field of view to be used by CDS. This would guarantee finding the target for all operations. However, the CDS field of view will vary, depending on the sequence of operation, from 4 x 4 arc minutes to 2 x 2 arc seconds, and one cannot expect to know the site to exactly 1 pixel. The smallest solar features (spicules, fibrils etc.) will always fall into a reasonable field of view, i.e. there would be no desire to select one specific spicule or fibril. The smallest rasters to which we may reasonably apply our criterion would, perhaps, be at about the 20 x 20 arc second level, thus demanding a pointing accuracy of 10 arc seconds.

The relative pointing of CDS and SUMER may be gauged by a comparison of images in identical lines. Large scale rasters should be performed at the same time by CDS and SUMER in these lines at a maximum of once per month.

CDS will carry a Sun Sensor to monitor the pointing of the experiment and to calibrate the coarse pointing occasionally. Calibrations of the pointing will have to be made occasionally by performing limb-crossing activities. SOHO will have a Fine Pointing Sun Sensor and data from this device will be available to the experimentors in the housekeeping telemetry.

8.8 Calibration Activities During Flight

Here, we are concerned with introducing a calibration plan for CDS operations. Table 8.4 lists CDS Studies which have or are being developed to tackle the requirements listed in the sections above. Details of the Studies can be found in the Appendix.

Table 8.4 - The calibration studies.

Study ID	**Details**	**Frequency**
SPECT	GIS Spectral Atlas - can be used for quiet Sun monitoring and wavelength calibration	once per week at least
NISAT	NIS Spectral Atlas - see note above	once per week at least
ICAL1	Intensity/Alignment cal. with GIS, NIS, SUMER, UVCS, EIT. [IJOP #1]	once every 2 weeks
ICAL2	Calibration against SEM using EIT as a transfer (GIS) [IJOP #2]	once every 2 weeks
AERON	GIS full Sun scan [IJOP #3]	once per month or less?
ALIGN	SUMER/CDS Alignment cal. [IJOP #4]	once per month
ICCAL	SUMER/CDS Intensity cal. [IJOP#5]	once per month
SERTS	CDS/SERTS Cross-calibration [IJOP#6]	when SERTS flies
NIMCP	NIS microchannel plate monitoring study	once per day, falling to once per week
GIMCP	GIS microchannel plate monitoring study	ditto
TEST3	CDS coarse pointing calibration	occasionally
TEST4	CDS fine pointing calibration	ditto

Where the Studies are included in a SOHO Intercalibration Joint Observing Programme (IJOP), the relevant number is given.