EUV Full Sun Imaging and Pointing Calibration of the SOHO Coronal Diagnostic Spectrometer

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Abstract. Although the field of view of the Normal Incidence Spectrometer (NIS) of the Coronal Diagnostic Spectrometer (CDS) is 4×4 arcminutes, it is possible to observe the full solar disk by forming a mosaic of images taken in succession. This paper describes just such a study which has been used to collect images of the Sun simultaneously in six wavelengths between 304Å and 630Å, and with a temperature coverage between 5×10^4 K and 2.5×10^6 K. A representative sample of the resulting images is presented. These data can be used to explore the origin of solar EUV variability, and examine large scale solar features. Another use of these data is to calibrate the pointing of the CDS Offset Pointing System (OPS), by comparing them against the SOHO Extreme ultraviolet Imaging Telescope (EIT) full disk images taken at the same time. Many joint observations are made with CDS and other SOHO instruments, and calibration of the pointing is crucial to the co-pointing of the instruments, and to the analyses of these data. Coalignment is done by fitting to a cross-correlation function, using an IDL procedure which can be applied to any CDS/NIS data set. The accuracy of an individual coalignment can be demonstrated to be in the range 1–2 arcseconds. The overall accuracy of the OPS calibration is ±5 arcseconds, mainly attributable to measurement error in the actuator positions. An onboard Spartan Intermediate Sun Sensor of the Lockheed design, which was intended to provide greater pointing accuracy, exhibits a time-varying calibration, possibly due to a gradual loss of sensitivity.

1. Introduction

The Coronal Diagnostic Spectrometer (CDS) is an instrument aboard the Solar and Heliospheric Observatory (SOHO). It uses a grazing incidence Wolter-Schwartzchild type 2 telescope to feed two spectrometers operating in the extreme-ultraviolet (151–785Å), to observe the solar corona and transition region. A complete description of the instrument can be found in Harrison *et al.* (1995).

The SOHO spacecraft attitude is three-axis stabilized, and maintained so that its optical axis points toward the photometric center of the Sun, with the vertical axis aligned with the planar projection of the solar north rotational axis (Domingo, Fleck, and Poland, 1995). The CDS instrument includes a number of mechanisms to allow it to off-point from the nominal spacecraft pointing. Coarse pointing is controlled by linear actuators attached to two of the six legs attaching CDS to the spacecraft. These mechanisms, referred to as the Offset Pointing System (OPS), allow CDS to be pointed up to $\pm 0.75°$, or 3 solar radii.

For a given OPS pointing, an internal mirror between the telescope and the slit allows one to scan in units of 2 arcsecond steps between ± 2 arcminutes, in the solar east-west direction. The pointing control in the solar north-south direction depends on which spectrograph is being used. The Normal Incidence Spectrograph (NIS) uses a slit 4 arcminutes in length oriented parallel to solar north. The Grazing Incidence Spectrometer (GIS) uses a pinhole aperture, which is capable of being moved by ± 2 arcminutes in the north-south direction. Thus, for either spectrometer, the instantaneous field of view available for any CDS raster is $4' \times 4'$.

The OPS left and right actuators were designed to position the CDS for observations to within ± 10 arcseconds of the desired location. (A large part of this error is due to hysteresis, i.e. mismatch between commanded position and actual position.) The solar coordinates of a particular observation are translated directly into the left and right actuator commands sent to CDS. The actual position of the CDS for the observation can be determined from the potentiometer readings of the OPS actuators and the SOHO spacecraft pointing, or from readings from the Spartan Intermediate Sun Sensor on CDS.

Many CDS observations are made in conjunction with other SOHO instruments, with ground-based observatories, and with other solar satellites such as Yohkoh and in the future the upcoming TRACE mission. It is necessary to obtain as good a model as possible of the OPS behavior in order to accurately position CDS for observations. It is also important to understand the relative accuracies of the OPS and Sun sensor systems in order to measure as accurately as possible where an observation really took place. This analysis seeks to address these questions.

2. The full Sun observations

In order to cover the complete solar disk with CDS, multiple rasters must be made. The maximum diameter of the photospheric disk as seen

Table I. Lines used in the CDS full Sun study. Associated ionization temperatures are derived from Arnaud and Rothenflug (1985), and Arnaud and Raymond (1992).

Ion	Wavelength (Å)	Temperature (K)
He I	584.34	-
He II	303.78 (second order)	5.0×10^4
O IV	554.52	1.6×10^5
O V	629.73	2.5×10^5
Mg IX	368.06	1.0×10^6
Fe XVI	335.40	2.5×10^6

from SOHO is about 33 arcminutes. A grid of 9×9 rasters, each 4'×4' in size, will thus not only cover the Sun, but also about 1.5 arcminutes above the limb. Three rasters can be omitted from each corner, as they are well off the limb, leaving a total of 69 rasters. The arrangement of the rasters is designed to minimize the number of mechanism movements—the first row of rasters are arranged from left to right, the second from right to left, and so on. To cover the 4'×4' field of view of each raster most efficiently, the NIS is used with the 4 arcsecond wide slit. Thus each raster consists of 60 exposures, and it takes a grand total of 4140 exposures to cover the Sun. The exposure time for each exposure is 3 seconds; with various overheads, the total duration of the full Sun study is just under 11 hours. All CDS sequences are given a 6–8 letter acronym for ease of identification. In this case, the study has the acronym "FSUN".

With a 3 second integration time, only the strongest lines in the NIS spectrograph can be observed. Even so, a good range of temperatures can be covered. Table I lists the lines observed in the full Sun measurements, and Figure 1 shows a representative sample of images. A more detailed image of the Sun in the He I λ584Å line is shown in Figure 2. Although these images are built up from a large number of exposures, all of the lines are observed simultaneously in each exposure. This means that data from one line at a given spatial location is directly comparable to all the other lines at the same location.

One can compare this temperature coverage to that of the Extreme ultraviolet Imaging Telescope (EIT) instrument, also aboard SOHO (Delaboudinière *et al.*, 1995). The λ304Å band is observed by both instruments; the other three EIT bands range in temperature from 1.3×10^6 K to 2.0×10^6 K. Thus, the CDS observations form a complementary set to those of EIT by filling in the gap between 5.0×10^4 K

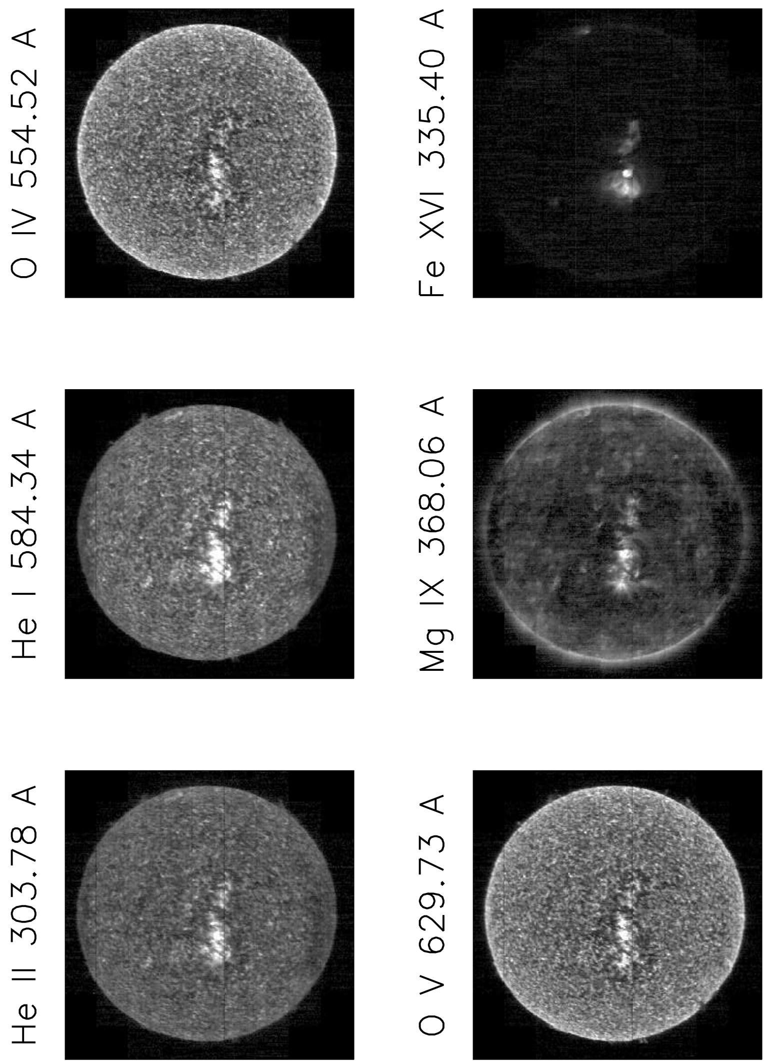


Figure 1. Images of the full Sun as observed by the CDS NIS instrument on 12 May 1996.

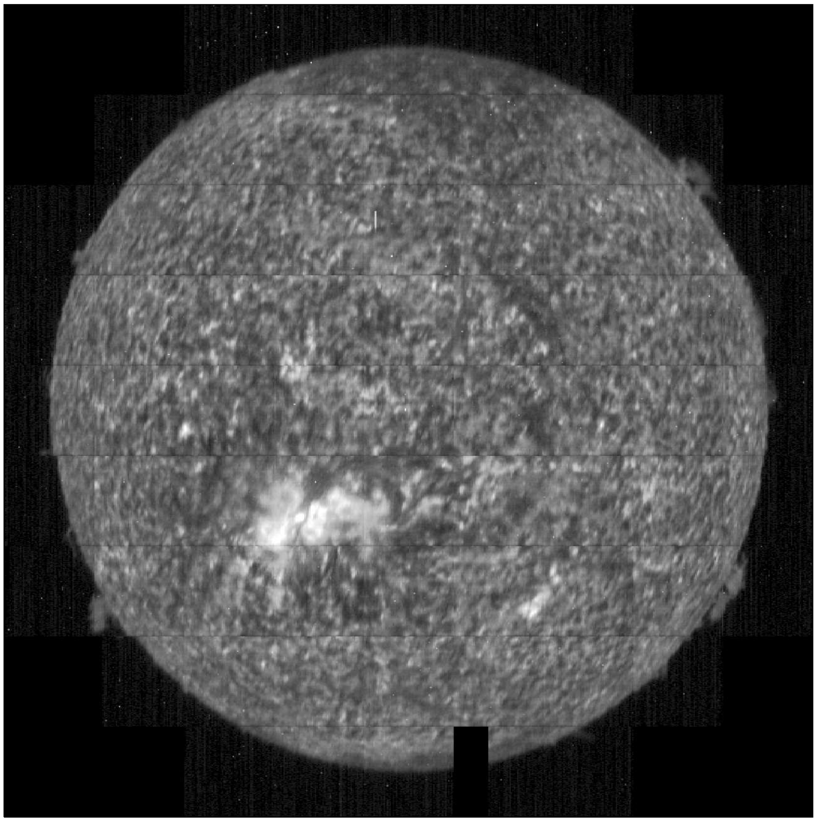


Figure 2. High resolution image of the full Sun in the He I λ584Å line, as observed by the CDS NIS instrument on 28 August 1996. The scan pattern is clearly visible.

and the hotter lines seen by EIT, as well adding the even hotter Fe XVI λ335Å line in active regions. Possible uses of these data include

- Understanding the origin of solar EUV variability.
- Relating large scale coronal structures to features in the lower corona and transition region.
- The Sun as a star.

Some care must be exercised in analyzing this data. In order to stay within the CDS telemetry budget, the data were summed onboard over the line profile before transmitting to the ground. Hence, no line profile analysis is possible, and one cannot a priori distinguish between the contribution from the emission line itself, and the contribution from the background which is dominated by off-band scattering. This is particularly true for places where the emission is weak. For example, the image formed at the Fe XVI line can only be trusted to be representative of that ion in the bright areas of that image. The other lines in the full Sun observation are strong enough to overwhelm the background everywhere on the disk.

3. The Offset Pointing System

The principal reason for making full Sun observations is to calibrate the effect of the OPS on the pointing of CDS. Since CDS and EIT are both instruments aboard SOHO which observe the $\lambda 304$Å line, and since EIT observes the full solar disk in a single exposure, it is natural to use the EIT $\lambda 304$Å images to calibrate the CDS pointing.

Before flight, a mathematical model was developed to describe the effect of the OPS (Richards 1990, Carter 1994). Six supports attach CDS to the SOHO spacecraft. Each support is free to pivot at either end, and thus restricts motion only in the direction along the support. The supports are arranged so that each restricts one of the 3 rotational and 3 translational degrees of freedom. The two rear supports are equipped with actuators which allow their lengths to be varied. This allows the yaw x and pitch y of the instrument to be modified, while the other supports constrain the other degrees of freedom.

For a given position of the left and right actuators l, r, the CDS pointing x, y is modeled by the equations

$$\begin{aligned}
\Delta l &= l - l_0 \\
\Delta r &= r - r_0 \\
\Delta m &= \Delta l - \Delta r \\
\Delta p &= \Delta l + \Delta r \\
x &= -k_x \left(\Delta m + \frac{\Delta m \Delta p}{R} \right) \\
y &= -k_y \left(\Delta p - \frac{\Delta m^2 + \Delta p^2}{2R} \right)
\end{aligned} \tag{1}$$

where l_0 and r_0 are the actuator positions representing disk center, k_x and k_y are proportionality constants in units of arcseconds/step, and R is a term representing the second order behavior. The results x and y are the pointings of CDS offset from disk center in the E-W and S-N directions respectively, where x increases towards solar west and y increases towards solar north.

The procedure for calibrating the pointing of CDS is to determine the x, y pointing individually for each raster in the full Sun study by cross correlating it with an EIT image taken close in time. These pointings, together with the OPS l, r values from the CDS telemetry, are then fed into the above equations to derive a least-squares fit for the parameters l_0, r_0, k_x, k_y, and R.

4. Cross correlating with EIT

The procedure for cross correlating the individual CDS rasters with the EIT full Sun images is as follows. First, the absolute pointing of the EIT image must be established. This is done by fitting a circle to the limb. Rather than allowing it to be a free parameter, a standard plate scale was established for the EIT images, consistent with the limb having a solar radius of 696,000 km. This is a source of error, because the apparent limb of the Sun in this region of the spectrum is above the photospheric limb. However, all the SOHO pointing software is designed to employ a single solar diameter, regardless of apparent changes in solar disk size with wavelength, so it was decided to let this small error remain. It can be removed at a later date simply by multiplying k_x and k_y by a correction factor.

Once the EIT pointing is established, the nominal pointing of the CDS raster is corrected for solar rotation using standard IDL software to the time of the EIT image, so as to determine the appropriate part of the EIT image to use in the comparison. The corresponding 4'×4' region is then extracted from the EIT data, and the two images are resampled to put them on the same scale. A cross-correlation matrix is formed, and the bi-lateral Gaussian function

$$G = A_0 + A_1 \exp\left(-(\frac{x - x_0}{A_4})^2 - (\frac{y - y_0}{A_5})^2 - A_6(x - x_0)(y - y_0)\right) \quad (2)$$

is fitted to the matrix to determine the position x_0, y_0 of maximum correlation. The resulting corrections are applied to the pointing of the EIT subimage, and the correction for solar rotation is applied in reverse to return to the time of the CDS raster. Rasters which include the limb are not included in the analysis, because of the difficulty of separating the effect on the correlation matrix due to the limb from the effects of solar rotation.

A possible source of error in this analysis is the correction for differential solar rotation to the time of the CDS raster. The algorithm used is taken from Allen, 1955. The amount of correction applied to the data under study ranges from 0–60 arcseconds, with an average of

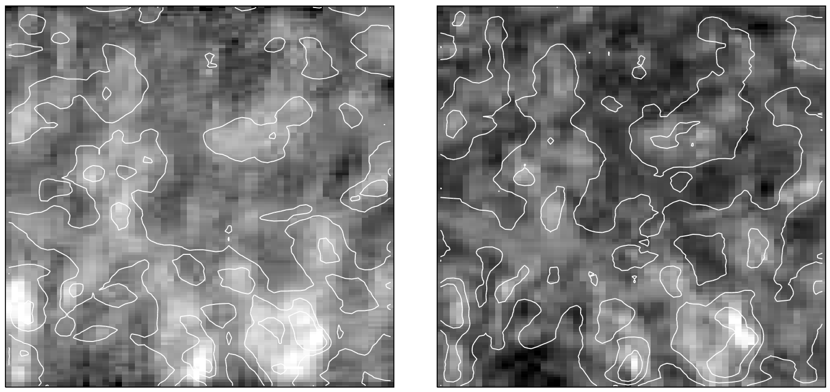
$\sim$30 arcseconds. If the algorithm was off by 1%, then this would lead to only $\sim$0.3 arcseconds error in the result. One indication that the rotation correction is not a significant factor in the result is that similar results are obtained with EIT images spaced six hours apart.

Figure 3 shows a typical result of the cross-correlation process. The He II λ304Å images proved particularly effective for co-alignment purposes, because of the well-defined supergranulation network which was visible everywhere on the disk. The EIT images used for the analysis were from the regular synoptic program. Typically, there were two EIT λ304Å images during a run of the full Sun study. Although for any CDS raster, the difference in time from the EIT full Sun image was generally several hours, a correlation still could be made—there would be temporal changes in the brightness of features, but the overall network structure would remain. Comparing an EIT image taken during the first half of the CDS full Sun study against all the CDS rasters gave the same result as using an EIT image from the second half. It was also found that correlating the He I λ584Å images from CDS against the EIT λ304Å images was equally effective, and gave the same results.

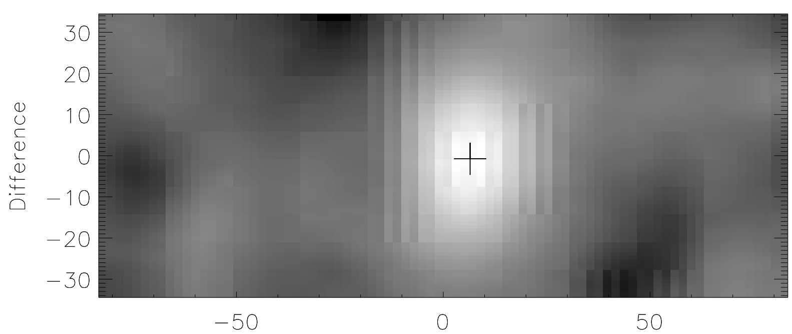
The procedure described above for coaligning CDS raster images with data from other telescopes has now been extracted into the IDL routine XCOR_CDS in the CDS software library. In that routine, an additional correction is made for the solar rotation during longer duration CDS rasters. (Although the complete full Sun study takes almost 11 hours, each raster only takes 10 minutes, so that the rotation during the time to accumulate the raster is not a significant consideration.)

5. Calibrating the OPS

A list of runs of the full Sun study is given in Table II. It is now part of the CDS synoptic plan to run this study once per month, to monitor for any changes in the pointing behavior. Analysis of these data sets leads to a consistent set of results for the parameters from equation 1. The most difficult parameters to pin down were l_0 and r_0. These parameters are most sensitive to small errors in determining disk center in the EIT images. It was decided to use the apparent location of the limb in the CDS images to determine the final values of l_0 and r_0. The daily CDS synoptic scans ("SYNOP", described in Harrison *et al.* (1995)) were used to determine the vertical position of disk center as seen by CDS, while the horizontal position was determined from the extreme left and right rasters in the full Sun scans. The coordinates of disk center l_0, r_0 were chosen to be consistent with both data sets. Putting this all



(a)



(b)

Figure 3. (a) Comparison of CDS and EIT data taken in the He II λ304Å line. The CDS image is on the left, and the EIT image is on the right. The EIT image has been resampled to the resolution of the CDS raster. Smoothed contours from the EIT image are overlayed on the CDS image, and vice-versa. (b) The cross-correlation matrix of the CDS and EIT images. The cross gives the fitted position of maximum correlation.

Table II. List of runs of the CDS full Sun study as of May 1997. Those marked with an asterisk (*) are incomplete.

Study counter	Start date/time
631*	1996/04/17 18:32
714	1996/04/24 07:01
2707	1996/05/12 02:55
3158	1996/06/12 17:04
3281*	1996/06/25 09:22
4185*	1996/08/14 06:33
4311	1996/08/21 12:32
4454	1996/08/28 13:17
4572	1996/09/04 06:26
4759	1996/09/16 05:10
5125	1996/10/05 13:02
5620	1996/11/03 06:33
5976	1996/12/01 06:27
6650	1997/01/08 06:26
6858	1997/02/02 06:41
7130	1997/03/01 11:58
7498	1997/04/02 06:31
7771	1997/05/04 06:49
7917	1997/05/16 00:34

together, the best-fit parameters to equation 1 are

$$\begin{aligned} l_0 &= 2034 \\ r_0 &= 2008 \\ k_x &= 0.953 \\ k_y &= 0.942 \\ R &= 5.69 \times 10^4 \end{aligned}$$

The average residual from the fit to equation 1 is about ± 5 arcseconds. Here, the residual is defined as the square root of the average square deviation in both the x and y directions combined. Several sources contribute to the total residual. One source is the uncertainty in the cross-correlation between the CDS and EIT images—the next section will show that this contribution is small. Another potential source is the uncertainty in the measurement of the OPS l and r positions—section 7 will demonstrate that this factor probably dominates. A third may arise if there are additional factors in the pointing calibration that are not accounted for in equation 1.

6. Calibrating the Sun sensor

The CDS instrument also includes a Spartan Intermediate Sun Sensor (SISS) mounted to the front bulkhead. The Sun sensor is of the Lockheed design, and was built by the Physical Sciences Laboratory at New Mexico State. The same technique used to calibrate the OPS can also be used to calibrate the signals from the SISS. The relationship between the SISS voltage and the CDS pointing angle is given by the equation

$$\begin{aligned} x &= A_0 + A_1(V_x + A_4|V_x|) + A_2 \arctan\left(A_3 A_1(V_x + A_4|V_x|)\right) \qquad (3) \\ y &= B_0 + B_1(V_y + B_4|V_y|) + B_2 \arctan\left(B_3 B_1(V_y + B_4|V_y|)\right) \end{aligned}$$

The parameters A_0, A_1, B_0, and B_1 are inversely proportional to the total flux of the source, and thus vary approximately as the square of the distance to the Sun—the remaining parameters describe the sensor itself (Welsh, 1987).

The residuals to the fits to equation 3 are much lower than those to equation 1; typically about 1.5 arcseconds in x and 1.1 arcseconds in y. Thus, the errors in the cross-correlation between the CDS and EIT images must be at least this good.

Unfortunately, the calibration of the SISS appears to be a time-varying function. Although a good fit can be achieved for any given date, the calibration curve changes significantly, in a way that cannot be explained by variations in the incident intensity. A good way to characterize this variation is to examine the slopes of the curves at $V = 0$. This is demonstrated in Figure 4 for the x dimension—the y calibration curve behaves similarly. This behavior is consistent with a gradual loss of sensitivity in the Sun sensor.

7. Comparing the primary and secondary OPS sensors

In the previous section, it was shown that the uncertainty in the cross-correlation between CDS and EIT is no greater than 1–2 arcseconds. We now consider the question of the uncertainty in the measurement of the OPS l and r coordinates.

There are two sets of potentiometers used to measure the position of the OPS mechanisms, a primary set and a redundant set. They are mounted at different positions on the mechanisms, and hence do not give the same values. However, the difference between the primary and redundant readings can be used to explore the measurement uncertainty. Figure 5 shows the differences between the primary and redundant measurements of the OPS pointing for one of the runs of the full Sun

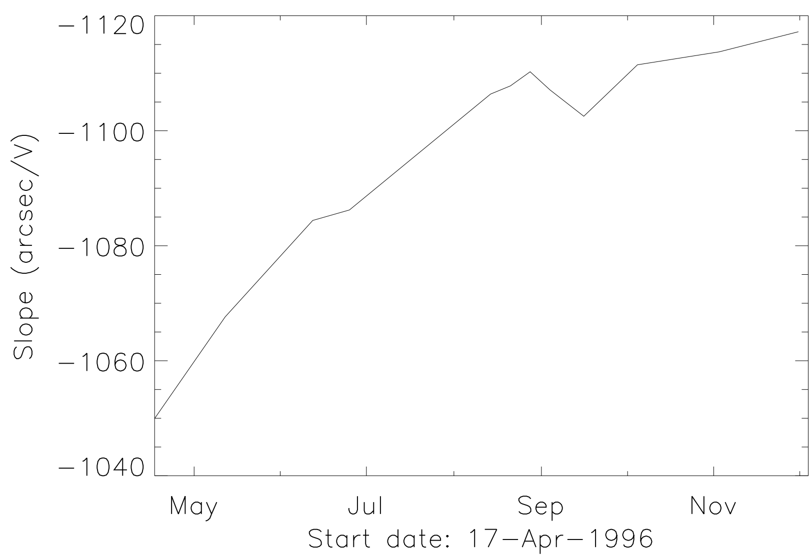


Figure 4. The slope of the calibration curve for the Sun sensor yaw (x) as a function of date. The part of the variation due to the spacecraft orbit has already been removed.

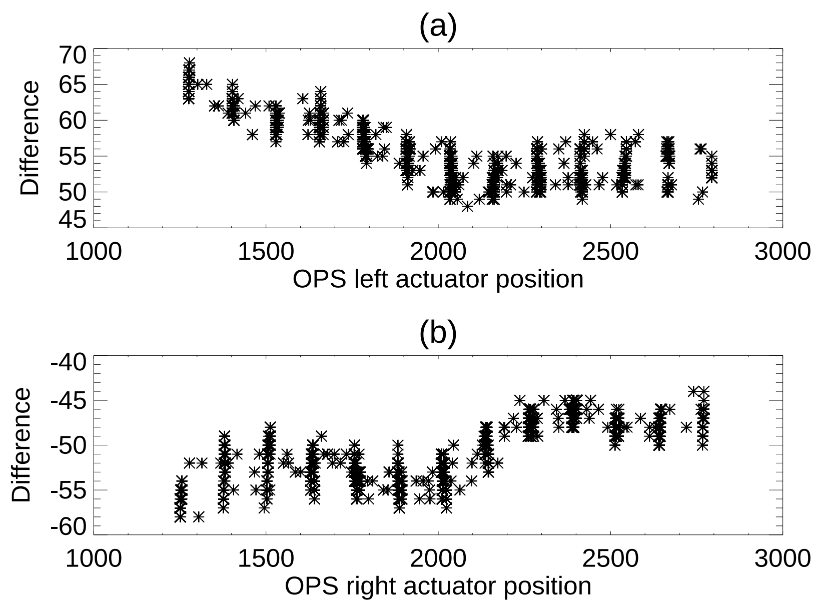


Figure 5. Measurements of the differences between the primary and redundant measurements of the OPS actuators, plotted against the primary measurement. The two graphs are for the (a) left, and (b) right actuator.

study. Two things are evident from these figures. First of all, the differences between the primary and redundant potentiometers are not constant, but vary with actuator position. Also, it is evident that there is some spread in difference of on the order of 5–10 steps. The conclusion is that the measurement error must be on this order. Assuming that the error is equally shared by both the primary and redundant potentiometers, and considering that a movement in either actuator results in a motion of $\sim$1.3 arcseconds, one can translate this uncertainty into a pointing uncertainty of 3.5–7 arcseconds. Thus, it is apparent that the major source of the residual in the pointing calibration discussed in section 5 is due to measurement uncertainty in the OPS.

It should be pointed out that the specifications for the OPS called for a pointing accuracy of 10 arcseconds. This has clearly been achieved.

8. Pointing stability

The pointing of CDS depends on the pointing of the SOHO spacecraft. The OPS can only offset from the spacecraft pointing. If there is a change in the pointing of the spacecraft, then that will be reflected in the pointing of CDS. One way that this effect can be monitored is by using the daily runs of the synoptic program. Figure 6 shows the apparent vertical position of solar disk center as derived from fits to the limb at the poles. There is a lot of scatter in the data, at least partially caused by solar features, but some long term effects are evident at the level of a few arcseconds. It appears that there was a slow rise in the apparent Sun center position of about 2 arcseconds from May to the beginning of September, 1996, and then a slow drop of about 3–4 arcseconds. Determining whether or not these shifts are due to the pointing of the spacecraft, or to changes within the CDS instrument would require comparison with data from other instruments.

The same analysis can be performed for the horizontal direction using the full Sun study. The results are shown in Figure 7. The interpretation of this data set is less clear than that of Figure 6, since the measurements are much sparser, but there does not appear to be any significant horizontal drift.

We have compared the data in Figures 6 and 7 with similar data from the SOHO Michelson Doppler Imager (DeForrest, 1997). Both instruments see long-term changes on the order of a few arcseconds. However, the drifts seen by the two instruments do not correspond to each other, and thus do not appear to be from a common cause.

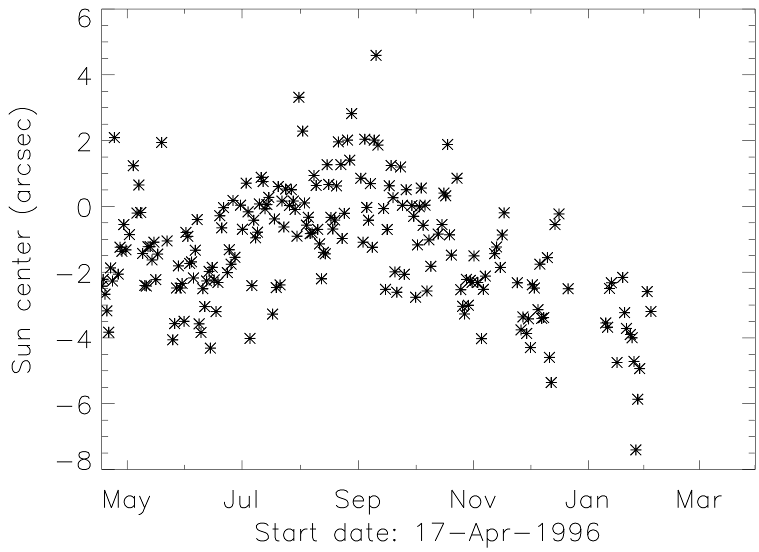


Figure 6. The apparent vertical position of Sun center derived from the daily synoptic program.

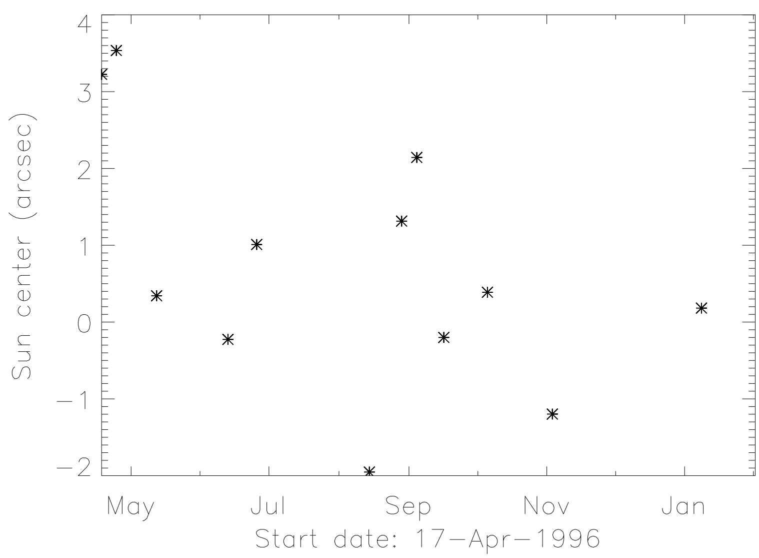


Figure 7. The apparent horizontal position of Sun center derived from the CDS full Sun program.

9. Conclusions

We have shown that CDS raster data can be coaligned with EIT 304Å images to 1–2 arcsecond accuracy. To some extent, the accuracy is driven by the size of the raster area. The cross-correlation technique works more efficiently with a 4'×4' raster than it would with a smaller area. This cross-correlation can be done with either He II λ304Å, or with He I λ584Å.

The pointing accuracy of the CDS Offset Pointing System is somewhat lower, $\sim$5 arcseconds. The bulk of this residual is attributable to measurement errors in the potentiometers used to determine the pointing. The design goal of 10 arcsecond pointing accuracy has been achieved.

The accuracy of the Spartan Intermediate Sun Sensor is very high for time periods on the order of hours, and is well suited for characterizing any jitter the instrument may encounter. However, its calibration has shown a slow drift during the mission, which limits its use for determining the absolute pointing.

In addition to its use for calibrating the CDS pointing, the full Sun observation program described here forms a useful data set for characterizing the global properties of the Sun between 5.0×10^4 K and 2.5×10^6 K.

10. Acknowledgements

The EIT image shown in Figure 3 was provided courtesy of the EIT Consortium.

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