INTERCALIBRATION OF CDS AND SUMER

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ABSTRACT

The outcome of the Joint Observing Programme (JOP) Intercal_01, which is the intercalibration of the SUMER (Solar Ultraviolet Measurements of Emitted Radiation) instrument (detectors A and B) and the two CDS (Coronal Diagnostic Spectrometer) instruments, the Normal Incidence Spectrometer (NIS) and the Grazing Incidence Spectrometer (GIS), is presented. Recent calibration updates of both instruments have been employed, and the results indicate a very good correlation and agreement of the measured radiances within the individual uncertainties.

Key words: CDS, SUMER, cross-calibration.

1. INTRODUCTION

The radiometric intercalibration between the extreme and far ultraviolet spectrometers CDS and SUMER has been introduced in previous papers (*Pauluhn et al.*, 1999, 2001). Here we report on a comparison of measurements of the SUMER instrument and the Normal Incidence Spectrometer (NIS) as well as the Grazing Incidence Spectrometer (GIS) of CDS using the most recent calibrations (see also *Wilhelm et al.* (2002) and *Lang et al.* (2002)). SUMER (*Wilhelm et al.*, 1995) is a stigmatic normal incidence telescope and spectrometer using two superposed orders of diffraction to cover the wavelength range from 46.5 nm to 161.0 nm. Two identical detectors (A and B) can be used for observations in their common wavelength range below 147 nm. The CDS instrument (*Harrison et al.*, 1995) is a double spectrometer, combining the wide wavelength range of a grazing incidence device and the stigmatic imaging performance of a normal incidence instrument to cover the wavelength range from 15 nm to 80 nm. Both, the NIS and the GIS are fed simultaneously through a common slit by a grazing incidence telescope.

SOHO's intercalibration JOP Intercal_01 includes the simultaneous observation of quiet areas near Sun centre in the chromospheric line He I 58.4 nm and the two coronal lines Mg X at 60.9 nm and 62.4 nm by SUMER and CDS-NIS, and in the 77.0 nm Ne VIII line by SUMER and CDS-GIS. Later, the O V line at 63.0 nm was also included in the SUMER and CDS-NIS comparisons. After a description of the data reduction (Section 2), we compare the average absolute radiances of SUMER and CDS-NIS and CDS-GIS, respectively, for the entire period of the intercalibration observing programme (Section 3). A summary of the results and conclusions are given in Section 4.

2. DATA REDUCTION

2.1. The SUMER Data

The data reduction applied to the SUMER data in this study has been performed as described by *Pauluhn et al.* (2001), the only differences being the radiometric calibration factors, so that we restrict ourselves to a brief summary. An area of 60″×300″ was registered by a raster scan of the telescope with a step size of 0.76″ in east-west direction. After November 1996, raster scanning (in normal-current mode) was stopped and the scans were (apart from few dedicated measurements) limited to the drift of the solar surface across the slit due to solar rotation. Thus the area sampled by solar rotation was 3.5″×300″. Each raster was registered for 21 min 16 s, being composed of 80 exposures of 16 s each. The SUMER data were corrected for the flatfield, the geometric distortion, and for detector electronics effects such as dead-time and local-gain depression. The radiances have been obtained by fitting Gaussian functions and a linear background to the line profiles. Only the area under the Gaussian representing the main spectral line is considered. From March 1996 to August 1996 SUMER used its detector A, from September 1996 un-

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til June 1998 SUMER used its detector B, and following the loss and recovery of the spacecraft, from November 1998 to July 2000, SUMER alternately used both detectors. The post-recovery data have been corrected for the detector responsivity-loss following *Schühle et al.* (2000), using the factors 1.36 for 58.4 nm, 1.40 for 60.9 nm, 1.30 for 62.4 and 63.0 nm, and 1.60 for 77.0 nm after employing the SUMER SolarSoft programme `radiometry.pro` with the keyword `/before`. The relative standard uncertainty for SUMER's radiometric calibration is 20 % pre-accident, and 36 % post-recovery (*Pauluhn et al.*, 2001; *Wilhelm et al.*, 2002).

2.2. The CDS-NIS Data

The normal incidence stigmatic spectrometer (NIS) has two toroidal concave gratings with different ruling densities which are mounted side by side and slightly tilted with respect to each other. They disperse two different wavelength bands (NIS-1, NIS-2) one above the other onto the same detector. The data of JOP Intercal_01 reported here have been measured on NIS-2 using a slit of angular dimensions $4'' \times 240''$. Images are made by moving the slit perpendicular to its long axis in steps of $4''$, producing $60'' \times 240''$ raster scan images, consisting of arrays of 15 by 143 spatial pixels. The spatial pixel size along the slit corresponds to $1.68''$. The exposure time at each location was 80 s, resulting in a total accumulation time of 20 min for one raster. The main steps of the CDS data reduction consisted of correcting for burn-in and flatfielding. The images corresponding to the total line radiation were obtained by integrating a Gaussian fit in exactly the same way as with the SUMER data. For the CDS-NIS spectrometer the post-recovery line profiles exhibit wings of different strength on each side of each spectral line. This change is attributed to the prolonged heating causing an irreversible distortion in the instrument. Special fitting routines have been developed to account for the changed profiles (*Thompson*, 1999). The relative standard uncertainties for the radiometric calibration of CDS are 20 % for the He I line and 30 % for the Mg X lines (*Pauluhn et al.*, 2001; *Lang et al.*, 2002).

2.3. The CDS-GIS data

In the grazing incidence spectrometer (GIS) light from the slit illuminates a spherical grating which is set at grazing incidence. Dispersed radiation from the grating is incident onto four separate one-dimensional detectors placed at fixed positions around the Rowland circle (GIS-1: 15.1 to 22.1 nm, GIS-2: 25.6 to 33.8 nm, GIS-3: 39.3 to 49.3 nm, and GIS-4: 65.6 to 78.5 nm). For a description of the GIS detectors, see e.g. *Breeveld et al.* (1992); *Breeveld* (1996). For the present observations a $4'' \times 4''$ slit was used to give a $32'' \times 32''$ raster. Each of the 64 observations lasted 20 s, yielding an observation time of 23 min 22 s including telemetry overheads. The GIS detector data need corrections for fixed pattern and ghost effects, electronics dead-time, background, burn-in and flatfield; the burn-in has just recently been implemented (*C. Foley*, personal communication, 2002). A thorough description of the GIS and its data reduction procedure is given in the CDS Software Notes 54 to 56 (*Bentley*, 1999; *Breeveld*, 2000a,b). The relative stabdard uncertainty in the laboratory radiometric calibration of GIS is 30 % (*Lang et al.*, 2000).

3. RESULTS

For the CDS-SUMER intercomparison we have to distinguish between three periods with different conditions. In Phase I (March 1996 to August 1996) we can compare quasi-simultaneous measurements of overlapping areas on the Sun. In Phase II (September 1996 to June 1998), only averages of the total radiances in the respectively scanned areas can be compared. This is the case also for the majority of the post-recovery measurements (Phase III, November 1998 to February 2001). Also, for most of the time (Phases II and III) the CDS instrument scanned a much larger portion of the Sun and consequently observed different features than SUMER and thus could record different radiances. Another source of uncertainty is the fact that, as the solar activity maximum approaches, it becomes more and more difficult to find truly quiet-Sun areas. An overview over the various temporal and spatial scales of solar variability is given by *Solanki* (2002).

3.1. SUMER and CDS NIS

Figures 1 to 3 display the time series of all available radiances averaged over the rasters made by the two instruments as part of the Intercal_01 campaign. The three different phases of the intercalibration campaign are separated by the vertical lines. Figure 1a shows the averaged radiances of all available measurements of Intercal_01 in He I 58.4 nm. Figure 1b shows the same but restricted to the measurements that were simultaneously obtained by both instruments. Only these data are used for the comparisons between the two instruments, to keep the influence of the inhomogeneity and intrinsic variability of the solar radiation at a minimum. In Figures 2 and 3 the same quantities are depicted for the Mg X 60.9 nm line and the Mg X 62.4 nm line, respectively. The measurements of day 1165 (June 1999) and day 1565 (July 2000) were made off disk centre and extrapolated to centre values, according to the centre-to-limb variation described by *Wilhelm et al.* (2000). Especially in the coronal lines the variability increases significantly during Phase III, and at least the data recorded on days 1165 (June 1999) and 1451 (March 2000), as well as the last measurements (February 2001) contain parts of active regions.

In order to find out whether the time variability of the signals is solar or instrumental, we calculate the correlation between the two time series of the quasi-simultaneous measurements. High correlation indicates that the variability is solar rather than instrumental. For the He I 58.4 nm line the correlation of the time series of the CDS and SUMER measured radiances (averaged over the corresponding rasters) 0.84, 0.57, and 0.94 for the three phases independently. The correlations for the Mg X 60.9 nm line are 0.94, 0.84, and 0.87, while for Mg X 62.4

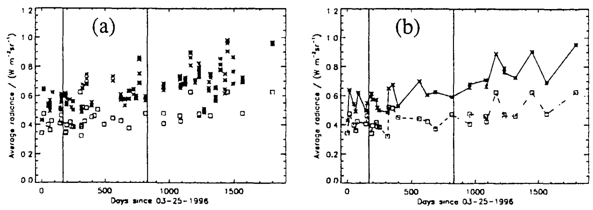

Figure 1. Spatially averaged radiances in He I 58.4 nm measured with CDS (stars) and SUMER (squares). The three phases of the intercalibration record (SUMER detector A, SUMER detector B, post-recovery, A and B) are separated by vertical lines. a) All available data. b) Simultaneous measurements of SUMER and CDS.

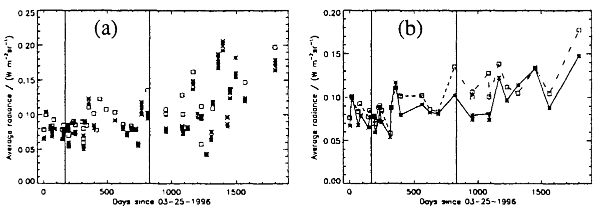

Figure 2. Radiances in Mg X 60.9 nm, see Figure 1 for details.

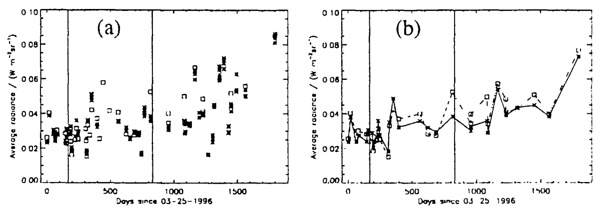

Figure 3. Radiances in Mg X 62.4 nm, see Figure 1 for details.

Table 1. Average relative differences between the CDS and SUMER time series ⟨CDS-SUM⟩/⟨CDS⟩ (in %). Columns A and B give the differences as calculated using the individual correction factors for SUMER, and using the average factor of 1.45, respectively.

wave-length / nm	Mar 96– Aug 96 (I)	Sep 96– Jun 98 (II)	Nov 98– Feb 01 (III) A	Nov 98– Feb 01 (III) B
58.4	23 ± 5	28 ± 9	34 ± 5	30 ± 5
60.9	-13 ± 8	-12 ± 11	-19 ± 19	-23 ± 19
62.4	-7 ± 9	0 ± 16	-11 ± 11	-24 ± 11
63.0	–	–	-17 ± 19	-31 ± 19

nm they are 0.92, 0.84, and 0.97. During the measurements of Phase I, raster scans over an area of 60″×300″ (SUMER, detector A) and 60″×240″ (CDS) were made and the common field of view was determined for the comparison. During Phase II, when SUMER's detector B was used, and later, the conditions for a comparison were not as good as before because SUMER's field of view was restricted to an area of about 3.5″×300″. This explains the lower correlation of the two time series over this period. Especially in the He I line, which shows the network very clearly, the correlation of the SUMER and CDS averaged radiances drops significantly during the second half of Phase II. In the post-recovery Phase III SUMER was also not scanning most of the time apart from two days when its scanning mechanism was operated in a high-current mode. Although in Phase III the conditions of both instruments have changed considerably, the correlation of the two instruments remains surprisingly high. The correlation between the two time series (corrected as described earlier) for the *entire* period of intercalibration measurements (Phases I to III) amounts to 0.85, 0.90, and 0.94 for He I 58.4 nm, Mg X 60.9 nm, and Mg X 62.4 nm, respectively. In Table 1 the average relative differences $\langle \mathrm{CDS}_{phase_i}\text{-}\mathrm{SUMER}_{phase_i} \rangle / \langle \mathrm{CDS} \rangle_{phase_i}$ of the three time periods are given. In the Mg X lines and in the O V line the uncertainty of this average difference is rather large. In the last column of Table 1 additionally the relative differences as obtained using the average SUMER post-recovery correction factor, which is implemented in the SUMER SolarSoft programme `radiometry.pro`, are given.

Note that apart from including one additional measurement (data of 26 February 2001) we used an updated and improved calibration for CDS as well as for SUMER, and therefore the results differ from the earlier ones described in *Pauluhn et al.* (2001) although the data analysis has been exactly the same. It is also noticeable that using the new calibrations, SUMER measures higher radiances in all lines apart from He I. In the He I line at 58.4 nm CDS measures 30 % higher radiance values than SUMER. For the O V line at 63.0 nm only post-recovery measurements were available within the intercalibration data set. All radiance values of both instruments fall well into the range of their combined uncertainties.

3.2. SUMER and CDS GIS

Figure 4 displays the time-series of all available radiances averaged over the rasters made by the two instruments as part of the Intercal_01 campaign. The vertical lines indicate the time of the spacecraft loss-of-attitude. Figure 4a depicts all available averaged radiances of the CDS-GIS and SUMER measurements, Figure 4b shows the simultaneous averaged radiances. Whereas the SUMER data are available from March 1996, the earliest data of the CDS-GIS are from May 1996. The average ratio of the

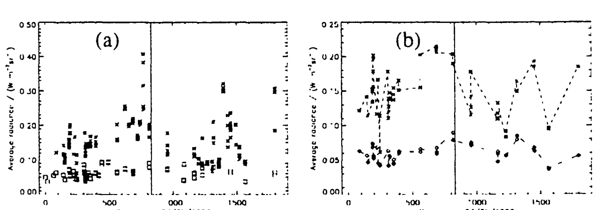

Figure 4. The spatially averaged radiances in Ne VIII 77.0 nm measured gv with CDS GIS-4 (stars) and SUMER (squares). The vertical lines indicate the date of the loss-of-contact with the SOHO spacecraft.

GIS to the SUMER average radiances amounts to 2.6 ± 0.9 before SOHO's loss-of-attitude and 2.1 ± 0.7 afterwards. The difference between the pre- and post-accident ratios can have various reasons. Firstly, it can be a purely statistical effect (note the relative standard uncertainties of 35 % in the weighted averages of the ratios), for instance induced by the selection of the data points, that is, the sampling of the intercalibration measurements. The SUMER post-recovery correction factor at 77.0 nm (1.60) could be too high. Using the averaged correction factor of 1.45 the average post-recovery ratio of GIS and SUMER is 2.4. Assuming that the GIS responsivity has not changed due to the SOHO accident, a factor of 1.3 for the SUMER post-recovery correction would give a consistent offset for the GIS and SUMER measurements at 77.0 nm before and after the SOHO loss-of-attitude. Another possibility for a different offset before and after the loss-of-attitude would be a slight systematic change of the GIS responsivity after loss-of-attitude, which is, due to the strong variability in this line, hard to detect. It is rather probable that the result is influenced by a combination of these effects. The large variability of the line intensity on short time-scales is clearly visible in the time-series. Even images registered shortly after each other (from twenty minutes to some hours) show differences in their averages of up to 20 % to 40 % in CDS-GIS, and up to 15 % to 20 % in SUMER. This difference in temporal variability is most likely due to the temporal and spatial differences in the raster scanning of both instruments (*Pauluhn et al.*, 2002). Successively restricting the SUMER image to smaller sizes showed that, for a SUMER image size reduced by a factor of approximately 4.5, both variabilites are in close agreement. The correlation of the time-series of the CDS-GIS and SUMER simultaneously measured averaged radiances in the Ne VIII line amounts to 0.49 before the SOHO accident. Afterwards, it amounts to 0.65 if the last data of 26 February 2001 are omitted, and 0.53 if these last data are included. Comparing normalized histograms of the distributions of radiance values of SUMER and CDS-GIS showed that, apart from the resolution-induced differences, both radiance distributions agree rather well.

4. SUMMARY AND CONCLUSIONS

The intercalibration between CDS and SUMER is reassessed, using the most recent available instrument calibrations. Some relatively large discrepancies were reduced, and for SUMER and CDS NIS, the radiance values lie within the range of their combined uncertainties. In the He I line at 58.4 nm, the CDS instrument measures on average 30 % higher values than SUMER. In all other studied lines the SUMER measured radiances are higher than the CDS ones.

SUMER and CDS GIS can be compared using the Ne VIII line at 77.0 nm, which CDS measures on the GIS-4 detector. The average ratio of GIS-4 to SUMER radiances is 2.6 for the data before loss-of-attitude and 2.1 afterwards. Revising the CDS-GIS responsivity to make GIS and SUMER intercalibration results agree means increasing the GIS responsivity at 77.0 nm by 2.4 ± 0.8. This is consistent with the change of a factor 1.9 at 73.2 nm suggested in *Del Zanna et al.* (2001) and with 2.1, which is their estimated result scaled to allow for the CDS burn-in corrections (wide slit in NIS and burn-in at 77. 0 nm in the GIS, both derived since their original data analysis) (*G. Del Zanna*, personal communication, 2002). Note that for both, CDS NIS-1 and GIS, the alignment of the laboratory calibration source was difficult to establish and that a factor greater than suggested here was applied to the NIS-1 responsivity (*Brekke et al.*, 2000; *Lang et al.*, 2002). An average increase of the GIS efficiency by a factor of 2.4 thus gives consistent results noting that the relative standard uncertainty of the GIS radiometric calibration is then estimated to 40 % pre-accident and 50 % post-recovery (*Pauluhn et al.*, 2002). These uncertainties have been calculated from the combined uncertainties of the data used in the comparison and the comparison itself, consisting of the single uncertainties of the data processing, burn-in, the weighted ratios, and the SUMER calibration. In general, the radiometric in-orbit comparison showed that the ratio between the responsivities of the two instruments remained constant with time until the SOHO accident. It has to be noted that the post-recovery radiance values are affected by larger uncertainties than those in the initial comparison, and that this period of the comparison is also subject to increased solar activity. Following the recovery of the spacecraft when the instruments had been exposed to extreme temperature conditions, the radiometric calibrations of both instruments are still maintained, although with higher uncertainty.

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