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The EUV spectrum of the Sun: long-term variations in the SOHO CDS NIS spectral responsivities

G. Del Zanna[1], V. Andretta[2], P. C. Chamberlin[3], T. N. Woods[4], and W. T. Thompson[5]

[1] DAMTP, Centre for Mathematical Sciences, University of Cambridge, Wilberforce Road, CB3 0WA Cambridge, UK
e-mail: GDelZanna@spd.aas.org
[2] INAF - Osservatorio Astronomico di Capodimonte, Naples, Italy
[3] NASA Goddard Space Flight Center, Solar Physics Laboratory, code 671, MD 20771 Greenbelt, USA
[4] Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado, USA
[5] Adnet Systems Inc., NASA Goddard Space Flight Center, code 671, MD 20771 Greenbelt, USA

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ABSTRACT

We present SOHO Coronal Diagnostic Spectrometer (CDS) normal incidence, extreme-ultraviolet spectra of the Sun taken from the beginning of the mission in 1996 until now. We use various methods to study the performance of the instrument during such a long time span. Assuming that the basal chromospheric-transition region emission in the quiet parts of the Sun does not vary over the cycle, we find a slow decrease in the instrument sensitivity over time. We applied a correction to the NIS (Normal Incidence Spectrograph) data, using as a starting reference the NIS absolute calibration obtained from a comparison with a rocket flight in May 1997. We then obtained NIS full-Sun spectral irradiances from observations in 2008 and compared them with the EUV irradiances obtained from the rocket that flew on April 14, 2008 a prototype of the Solar Dynamics Observatory EVE instrument. Excellent agreement is found between the EUV irradiances from NIS and from the EVE-prototype, confirming the NIS radiometric calibration. The NIS instrument over 13 years has performed exceptionally well, with only a factor of about 2 decrease in responsivity for most wavelengths.

Key words. Sun: corona – techniques: spectroscopic

1. Introduction

The SOHO Coronal Diagnostic Spectrometer (CDS) is composed of a normal incidence (NIS) and a grazing incidence spectrometer (GIS) (Harrison et al. 1995). With a few minor gaps, CDS covers the important 15 nm to 80 nm EUV spectral range, of which the ranges 30.8 nm to 37.9 nm and 51.3 nm to 63.3 nm are covered at first order by the two NIS spectral channels (NIS 1 and 2, respectively). CDS has routinely operated from 1996 to now and is providing us the first opportunity to study extreme-ultraviolet (EUV) radiances and irradiances over a full solar cycle, from the previous solar minimum in 1996 up to now. As part of a programme of studying the EUV spectral radiance and its variation over the cycle, we have done a full analysis of the performance of the CDS instrument and its radiometric calibration as a function of time. This has taken a considerable amount of effort and several years.

After many attempts, we realised that the performance of the GIS was best obtained by studying *both* the synoptic radiance measurements of the quiet Sun *and* the behaviour of line ratios. The final results, published in Kuin & Del Zanna (2007), were that for many wavelengths there was no appreciable drop in responsivity. The strongest lines were, however, affected by gain depression.

The results for the NIS are presented in this paper. The in-flight radiometric calibration of any EUV instrument is a notoriously difficult problem. Ideally, a radiometric calibration should be done by using a ground calibration as a base against a standard such as synchroton emission. In-flight changes should be monitored with rocket flights carrying similar instruments and calibrated on the ground. In practice, only a few useful calibration "check-points" have been available over the years. The history of the CDS calibration is a complex issue, as our understanding of the instrument has evolved with time. Here, we provide a short description of the relevant key facts, but further details can be found in the Appendix and in the references.

About two years before launch, the CDS instrument was calibrated end-to-end at the Rutherford Appleton Laboratory (RAL) against a "transfer" source that was absolutely calibrated using synchroton emission. Details can be found in Lang et al. (2000). From launch, it became evident that large departures (factors of 2–3) from the pre-launch calibration were present for the NIS 1 channel and all the GIS channels. The version 1 of the "standard" (available through *SolarSoft*[1]) NIS calibration (released on September 16, 1996) applied a correction factor to the pre-launch calibration.

On May 15, 1997, a NASA/Laboratory for Atmospheric and Space Physics (LASP) rocket carried an EUV Grating Spectrograph (EGS) that had been calibrated against synchrotron emission. The radiometric calibration procedures are described in Woods & Rottman (1990) and Woods et al. (1998). The EGS produced a coarse irradiance spectrum. On the same day, a series of NIS radiance measurements were performed. NIS irradiances were estimated and compared to the EGS ones, as described in Brekke et al. (2000). This study produced absolute values of the in-flight NIS responsivities. For NIS 1, only one reliable measurement, at 36.8 nm, was possible. For NIS 2, a coarse wavelength-dependence was estimated. The comparison

[1] http://www.lmsal.com/solarsoft/

of the strongest line, the He I 58.4 nm, provided a responsivity of $(4.75 \pm 0.4) \times 10^{-4}$ events/photon. This comparison was the basis for the version 2 of the standard NIS calibration, released on December 23, 1998. The relative uncertainty was estimated to be between ±15% at 58.4 nm and ±25% at either end of the NIS 2 waveband.

A later comparison was made of spatially resolved spectral radiance measurements with those from the SERTS sounding flight of November 18, 1997 (Thomas 2002). This prompted the release of version 3 of the standard NIS calibration, released on February 28, 2000. Later, the comparison against the EGS rocket flight was redone by including an estimate of the long-term decrease in responsivity. This resulted in an enhanced (by 15%) responsivity of 5.4×10^{-4} events/photon for the He I 58.4 nm line. Various other adjustments were made, and a calibration for the NIS 2 in second order (IIo) was added on May 21, 2002, the latest (version 4) CDS standard calibration.

Del Zanna et al. (2001) obtained an independent radiometric relative calibration by studying line ratios in a large number of observations of various features of the EUV Sun. Long-term corrections were not applied. The observed line ratios were compared to theoretical and/or previously well-calibrated measurements. The responsivity at 58.4 nm of Brekke et al. (2000) was adopted as absolute reference. After two workshops held at ISSI, Bern (cf. Del Zanna 2002; Lang et al. 2002), the teams of the various instruments on-board SOHO converged to a consistent relative radiometric inter-calibration within 30% to 50%, at a few selected wavelengths, which was considered satisfactory.

Further EGS rocket flights were flown in 2002, 2003, and 2004 for the in-flight calibration of the TIMED SEE EGS (Woods et al. 2005) instrument. These data were not useful for the CDS calibration because of their low spectral resolution and limited overlap with NIS observations. Still, a comparison between the TIMED SEE EGS data and the NIS has been performed, and there are substantial differences that have not been resolved yet, even with the latest SEE version 10 data set.

The final calibration flight for the TIMED SEE EGS was flown on April 14, 2008, carrying the prototype of the Solar Dynamics Observatory (SDO) EVE instrument. It provided an excellent EUV spectrum (Woods et al. 2009; Chamberlin et al. 2009) with a resolution similar to that of NIS. No useful NIS observations were taken on the day of the rocket filght, so a direct cross-calibration is not possible, unfortunately. However, the spectrum turned out to be very useful for validating the NIS calibration, as described below.

In summary, apart from the pre-flight calibration, only two rocket flights in 1997 and 2008 provide a direct radiometric calibration of the NIS instrument against a standard. It is therefore necessary to measure the long-term decrease in responsivity over the years, which is the main focus of this paper. After testing various methods over the past few years (see, e.g., Del Zanna et al. 2005; Del Zanna & Andretta 2006), and in the absence of any further direct calibration rockets, we resorted to an approach similar to the one used by Kuin & Del Zanna (2007) for the GIS channels, i.e. see how radiances of the quiet Sun, obtained with various synoptic programmes, decrease with time.

Most of the emission lines observed by the NIS are formed in the chromosphere and transition region (TR). For these lines we assume in our approach that their irradiance variations during the solar cycle are essentially due to the presence of active regions, and therefore that the mean radiances in the quiet Sun are constant during an activity cycle. This assumption implies, in particular, that radiances in chromospheric and TR lines in the current minimum are essentially the same as during the previous minimum in 1996.

In fact, irradiance measurements obtained from the rocket flights in 1997 and 2008 tell us that EUV irradiances (and radiances) during the previous and the current minimum did not vary significantly within measurement uncertainties. Moreover, ground-based measurements of equivalent widths of photospheric and chromospheric lines (e.g. Ca II) over the "quiet Sun" (often Sun centre) have provided firm evidence that the basal photospheric-chromospheric emission has not changed over the past three solar cycles (Livingston et al. 2007, 2009). These types of measurements are independent of radiometric calibration issues, making them very reliable.

It is true that there have been some reports of variations in the EUV radiances of chromospheric-TR lines in the quiet Sun; however, we notice that they are small (of the order of 30%) when compared to the variations due the long-term degradation in the NIS spectra, which we characterise in this paper. We also notice that relative variations of 30% in EUV radiances are within uncertainties, given the intrinsic solar variability in small fields of view and the uncertainties in the in-flight radiometric calibration of any EUV instrument. For example, Schühle et al. (2000) report an increase in radiances in EUV lines measured with SOHO SUMER during the 1996 to 2000 period, when solar activity was increasing. The variations in coronal lines such as the Mg X 62.4 nm could have been affected by the increase in solar activity. The variations in the radiance of the chromospheric He I 58.43 nm line are at most 30%, although the scatter in the measurements is greater than that. Pauluhn et al. (2001), and Pauluhn & Solanki (2003) report a similar small variation of 22% in quiet Sun radiances of the He I 58.43 nm line measured with SOHO SUMER. Relative uncertainties in the SUMER calibration for data taken after June 1998 are 33 and 36% for detectors A and B (Pauluhn et al. 2001).

In Sect. 2 we briefly describe the NIS instrument and present the various synoptic radiance observations that we used to estimate the long-term corrections to the responsivity. In Sect. 3 we briefly describe the EVE prototype and present a comparison between the line irradiances obtained from it and those obtained from NIS observations, with all the various calibrations and corrections. In Sect. 4 we draw the conclusions.

2. The NIS instrument and the synoptic radiance observations

The CDS instrument consists of a Wolter-Schwarzschild type II grazing incidence telescope, a scan mirror, and a set of different slits. The NIS is composed of two normal incidence gratings that disperse the radiation into the NIS detector, mainly composed of a microchannel plate (MCP) and a charge-coupled device (CCD) known as the Viewfinder Detector Subsystem, or VDS. The gratings are slightly tilted to produce two wave-bands (NIS 1: 30.8 nm to 37.9 nm and NIS 2: 51.3 nm to 63.3 nm).

MCPs normally suffer a drop in gain owing to the exposure to solar radiation. For the NIS, this results in a depression at the core of the lines when one of the 2″ or 4″ slits is used (the so-called *burn-in* of the lines). This effect in the NIS spectra has been monitored since launch with the NIMCP study, as described in Thompson (2000) (also see below). The use of the wide 90″ slit (number 6) also causes a drop in the NIS responsivity with time. In contrast to the line core burn-in, this kind of efficiency loss affects wide regions of the detector and was thought to be the main cause for the long-term decrease in responsivity (Thompson 2006). We return to this point below.

In addition, the temporary loss of contact with SOHO in June 1998 permanently damaged the performance of some of its instruments. The spacecraft was successfully recovered in September 1998. The NIS post-recovery spectra present broadened and asymmetrical line profiles that, in particular for NIS 1, strongly reduce the spectral resolution. The spectral resolution in terms of full-width at half-maximum (*FWHM*) was ≃0.035 nm for NIS 1 and ≃0.05 nm for NIS 2 before the SOHO loss of contact.

The NIS instrument has obtained various types of routine radiance measurements over the years which we used to study the instrument's performance. The NIS provides radiances over a maximum field of view of $4' \times 4'$ by moving the scan mirror to produce contiguous images of one of the long slits (a "raster"). Telemetry constraints are such that only a small fraction of the data recorded on board are telemetered to the ground.

Routine radiance measurements over the quiet Sun have been taken with various programmes. Here we focus on the daily NIMCP "study" (Sect. 2.2). Daily synoptic radiance observations in a few spectral windows were taken regularly in a strip along the meridian with various variants of the CDS study SYNOP (Sect. 2.4). Radiance measurements over the whole Sun were taken quite regularly once a month or so after 1998 with the CDS study USUN (Sect. 3). They consist of 700 to 1000 single-slit exposures sampling the whole Sun in about 13 hours (see, e.g., Thompson & Brekke 2000, for details).

2.1. Data reduction

The bias of the CCDs is regularly monitored. We applied standard processing for the de-biasing and flat-fielding, using the CDS routine VDS_CALIB. Cosmic ray hits strongly constrain NIS observations, in the sense that exposure times cannot be too long. Cosmic ray hits were removed from the subsequent analysis. Many geometrical distortions of the NIS spectra are present (see, e.g., Haugan 1999). The main one is the slant in the spectra, i.e. that the dispersion direction is not parallel to the CCD rows. This was corrected by the CDS routine VDS_ROTATE.

NIS spectra contain a scattered light ("background") component, which is mostly concentrated in the network areas, but disappears in off-limb observations. It was therefore believed that most of this scattered light comes from the H I Lyα; however, this "background" is fairly constant in wavelength, and has similar values in the two NIS channels. The NIS 1 is affected by additional "background" components at the shortest wavelengths. This background component is subtracted from the narrow-slit spectra when measuring the line radiances with a fitting procedure.

All the lines in the NIS 2″ or 4″ slit spectra were fitted with simple Gaussian profiles, in the case of data prior the loss of contact of SOHO, and with properly broadened profiles (with software developed by WTT) afterwards.

2.2. NIS MCP test (NIMCP) and the new long-term corrections for the NIS degradation

The NIMCP standard observations consist of a sequence of narrow 2″ (number 4) and wide 90″ (number 6) slit exposures over a quiet-Sun region. After the basic data reduction described in Sect. 2.1, spectra have been averaged along the slit.

For the 2″ data, the burn-in in the core of the lines was corrected by using the standard software available within *SolarSoft*. These corrections are based on the line centre burn-in measured in the NIMCP 90″ data and are described in Thompson (2000). They were obtained from the analysis of data up to 2003, and an extrapolation was then applied. For the strongest lines, profiles were reconstructed with a relative uncertainty of a few percent. Figure 1 (top) shows the entire averaged 13 years of NIMCP 90″ NIS 2 data over the quiet Sun corrected for the narrow-slit burn-in (but neither for the wide-slit burn-in nor for the overall detector decay in responsivity, the effects being addressed in this paper). A few exposures with count rates that were too low or too high were removed from the data set, leaving over 1000 averaged spectra. The same Fig. 1 also shows three averaged spectra, taken near the beginning of the mission (May–June 1997), after SOHO loss during solar maximum (January–March 2001) and recently in April 2008. The overall decrease in the count rates in both 2″ and 90″ spectra can be seen in Figs. 1 and 2.

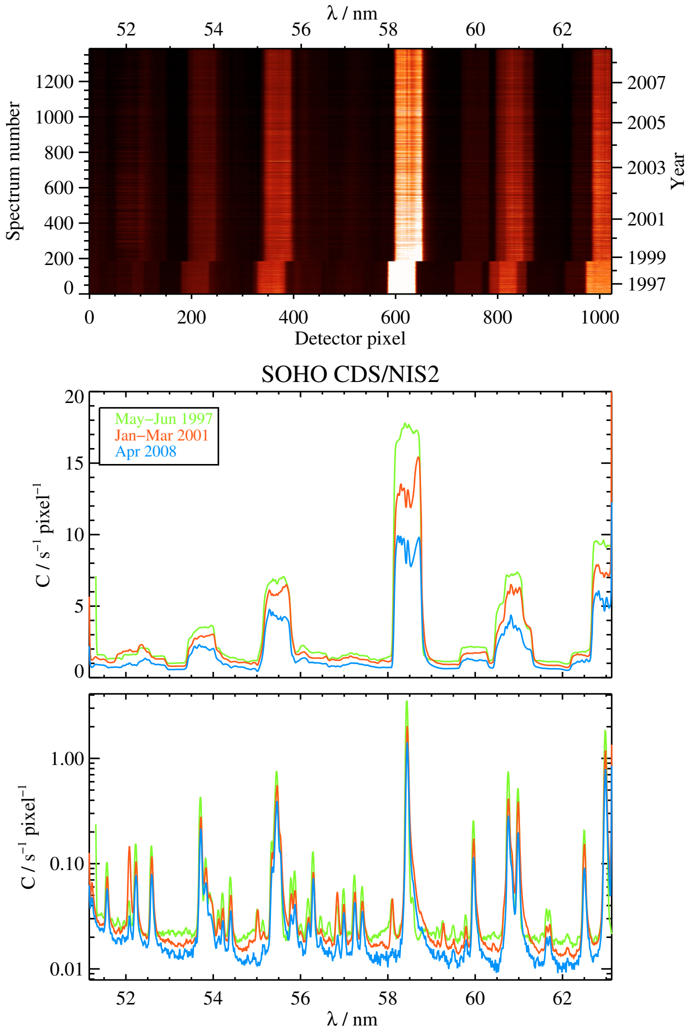

Fig. 1. *Top*: image of the 13 years of NIMCP 90″ NIS 2 data over the quiet Sun. *Middle*: a sample of averaged 90″ spectra at three different epochs. *Bottom*: the corresponding 2″ spectra. Units are average counts $C\ \mathrm{s}^{-1}$ pixel^{-1}.

The drop in count rates is more evident in the NIS 1 channel, as Fig. 2 shows. The Figure also shows the presence of the Fe XVI 33.5 nm and 36.0 nm lines during solar maximum, even in these "quiet Sun" observations, and the large drop in count rates in both the 90″ and 2″ spectra around these lines. The large broadenings in the NIS 1 lines occurred during SOHO loss.

The 90″ slit "smoothes out" the solar radiation, making it a good candidate for studying the overall decrease in responsivity.

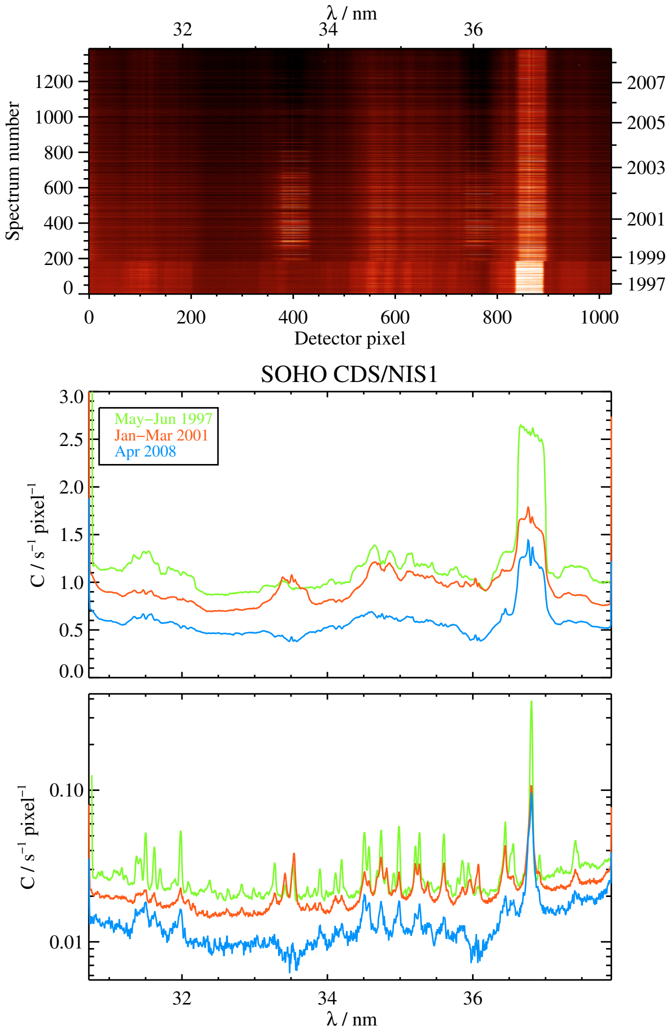

Fig. 2. As Fig. 1, but for the NIS 1 channel.

In the quiet solar spectrum, almost all the strong lines in the NIS 2 channel form at low (TR) temperature, and large parts of the NIS 1 channel are also dominated by spectral lines formed at temperatures at or below 1 MK. Therefore, as explained in Sect. 1, we do not expect large variations with the solar cycle in those spectra.

We therefore partitioned the NIS 1 and NIS 2 channels in wavelength bands centred on the various dominant lines, taking care to avoid regions with significant contributions from hot ($T > 1$ MK) lines, which have a strong variation with the solar cycle even in "quiet Sun" regions. We thus obtained averaged count rates from the 90″slit as a function of time. These rates are shown in Figs. 3 and 4. The vertical dashed lines mark a few significant events: the first VDS exposure (January 1996), the first NIMCP data set analysed (May 1996; taken as reference for our subsequent analysis), the date of loss of contact with SOHO (June 1998), and the return of SOHO to its normal mode (September 1998).

It is evident from these figures that the average count rates in all the selected bands display a similar, near-exponential decay with time, regardless of the temperature of the main lines contributing to each band, for a total variation of about a factor two from 1996 to date. The decrease is almost the same also in regions nearly void of spectral lines. This strongly suggests that the cause is an overall decrease in the responsivity, unrelated to the burn-in of the detector. The figures also show that a very different decrease in count rates occurred before and after the SOHO loss and that small differences in each spectral band are present. In the selected wavelength bands, there is no indication of increased count rates during the period of solar maximum, 2000–2002. Only the 55.0–55.9 nm band (middle-left panel of Fig. 4) shows some hint of a departure from this trend, but again, this effect is small when compared to the overall depression in average counts throughout the 13 years of data analysed. Such behaviour is of course consistent with our assumption that the "cool" lines dominating the count rates in the selected bands do not vary significantly over the solar cycle in the quiescent regions observed with the NIMCP programme.

The data points were then binned over a period of 90 days, obtaining an estimate of the mean and standard deviation in each time bin (points and bars in Figs. 3, 4). These binned data were fitted with a linear (before June 1998) or quadratic (after September 1998) polynomial in logarithmic scale (thick line in the figures). These fitted curves were in turn used to obtain long-term correction factors to the responsivity for each wavelength band, by assuming that the corrected count rates should be constant in time. The correction factors are only valid for the selected wavelength bands. Since the correction factors do not change much from band to band, it is however possible to interpolate them in the few regions of the detectors most affected by "hot" lines, which are strongly affected by the solar cycle. For example, total counts in bands 34.31–35.61 nm and 36.57–37.03 nm are reduced by factors 2.15 and 2.10, respectively, in January 2009 compared to May 1996. It is therefore reasonable to assume that a similar factor applies even at 36.0 nm, a region which we did not include in our analysis because strongly affected by a "hot" Fe XVI line.

To check the validity of the approach, we applied these corrections to three other independent datasets. Firstly, we applied these long-term corrections to the count rates in the NIMCP 2″ slit data. The uncorrected count rates show the same trends as those of the 90″ slit data, i.e., an overall drop of about a factor of 2 over 13 years. Once the corrections are applied, most lines show a constant trend. A sample is presented in Figs. 5 and 6. All the lines show a large scatter produced by solar variability, but no particular trends. Many of the weaker lines (e.g. He I 52.22 nm, O IV 60.84 nm) show some residual trends, which are due to the effects of strong nearby lines. The lines formed at temperatures higher than 1 MK (e.g. Si XII 52.06 nm and Fe XVI 33.53 nm) do show much higher counts during the period of solar maximum (2000–2003). Secondly, we applied the corrections to the daily synoptic observations. Before describing them, we now summarise the "standard" long-term corrections as available since 2002 through the standard CDS calibration software.

2.3. *The "standard" long-term corrections for the NIS degradation*

A preliminary "long-term standard correction" for the observed drop in NIS count rates as a function of time assumed that the main factor in the drop in the responsivity was caused by using the wide 90″ slit. This standard correction has been used until now within the standard analysis software, and is described in Thompson (2006). The method firstly assumed that the He I 58.4 nm radiance of quiet-Sun regions should be constant with time. Radiances from the long-term SYNOP (Sect. 2.4) data were used. This preliminary correction turned out to be quite accurate up to 2003, when observations were analysed. For later

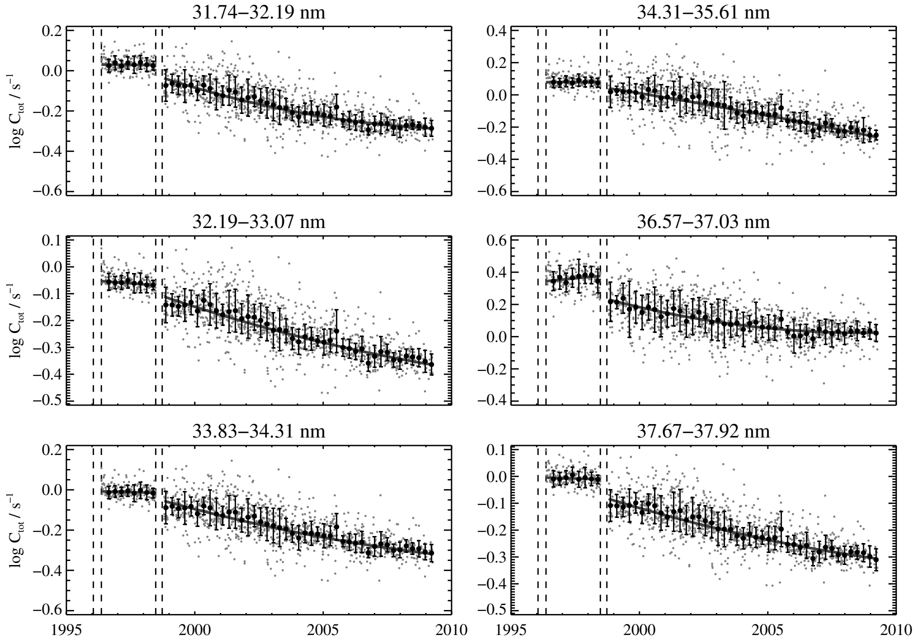

Fig. 3. Time-dependence of average radiances in various wavelengths from NIMCP 90″quiet Sun observations in the NIS 1 channel.

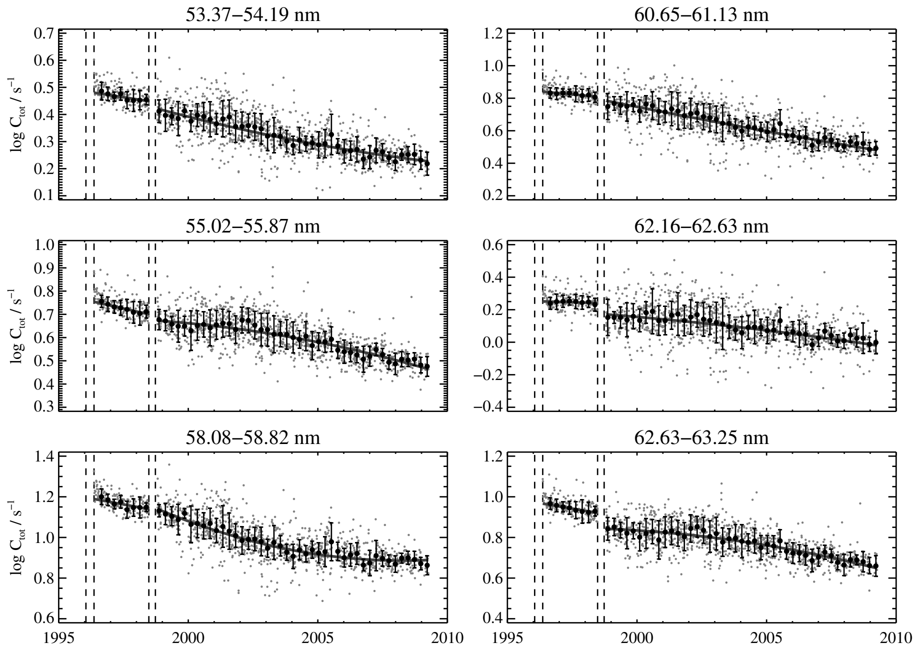

Fig. 4. As in Fig. 3, but for the NIS 2 channel.

dates, an extrapolation was adopted, which turned out to overestimate the correction by almost a factor of 2.

A preliminary correction for the other NIS wavelengths was then estimated by obtaining an average normalised wide-slit spectrum, and scale the corrections for the other wavelengths by assuming that the burn-in would follow this wide-slit spectrum. The time dependence of the scale factor was derived from an estimate of the total number of photons recorded by the instrument over time. Ideally, one could actually count the number of photons recorded by the instrument over time. In reality, however, only the data pertaining to a few spectral windows are routinely telemetered to the ground, so it is impossible to recover the history of the exposure to radiation.

In practice, it was assumed by Thompson (2006) that the accumulated photon count on the detector is proportional to the estimated accumulated exposure time. Such an assumption, however, would only be valid if the 90″ slit was used to observe only quiet regions. Indeed, during the early years of the mission, it was the policy to restrict use of the 90″ slit to quiet regions so as not to invalidate this assumption. However, over time this restriction was relaxed owing to the compelling science that could be achieved with the wide slit on active regions.

The assumption that the drop in responsivity has been caused mainly by the use of the wide 90″ slit predicts that the regions in the detector where the strongest lines fall should show a progressive decrease in responsivity, something which the data, with a few exceptions (such as the Fe XVI 33.5 nm and 36.0 nm lines, see Fig. 2), do not show as previously discussed.

We would also like to mention here that the standard long-term corrections were applied to a "quiet-Sun" dataset by Lang et al. (2007). The method was similar to that of Del Zanna et al. (2001) whereby ratios of radiances in various lines emitted by

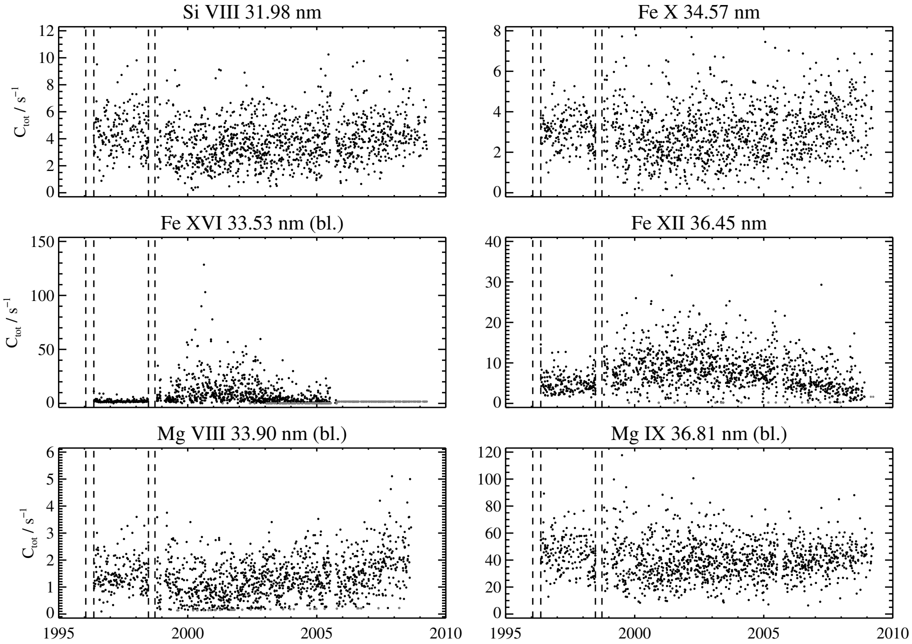

Fig. 5. Line radiances (units are photon-events) from NIMCP 2″ quiet-Sun observations in the NIS 1 channel after applying the long-term corrections.

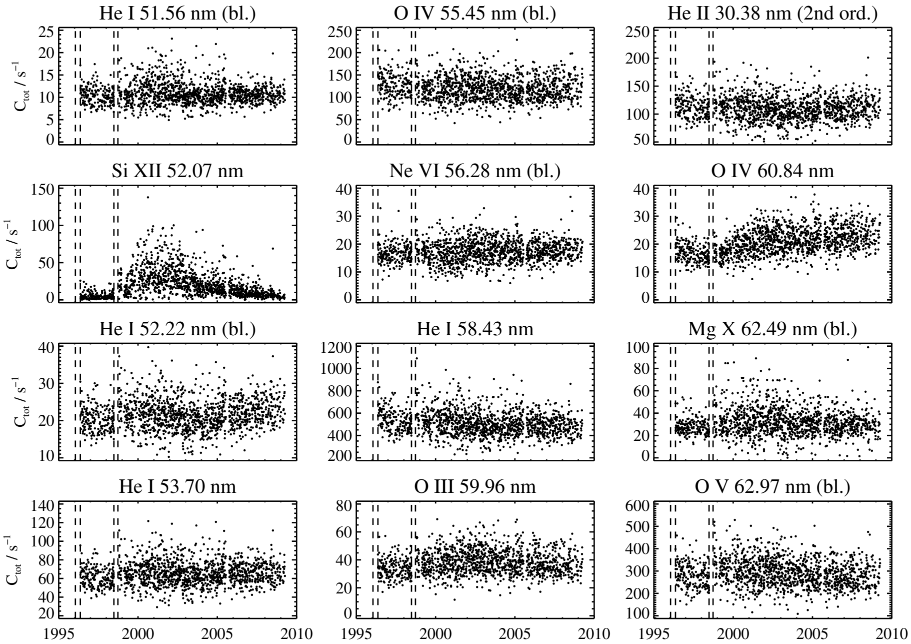

Fig. 6. Line radiances from NIMCP 2″ quiet-Sun observations in the NIS 2 channel, as in Fig. 5.

the same ion were studied. Mainly ratios that are expected to be constant were used. This study pointed out various problems with the standard long-term corrections; however, it could not characterise the overall variations of the detectors, and was limited by having only analysed data until 2002.

2.4. Daily synoptic observations (SYNOP)

NIS has observed with daily cadence a strip of the Sun along the meridian with nine $4' \times 4'$ rasters with the 2″ slit – study SYNOP (see, e.g. Fig. 7). Different versions of this study have been run over the years, with different line selections. However, all of them included the two brightest lines, the He I 58.4 nm and the O V 63.0 nm. These lines are formed at chromosphere-transition region temperatures, and their radiances are therefore less affected by the solar cycle. Indeed they are the only lines that could be used for our purposes. Other lines either had low count rates or were too broad for the narrow extraction windows.

We selected a (relatively small) sample of synoptic observations spanning the 13 years of SOHO operations, trying to uniformly cover the whole period but at the same time also avoiding days when strong active regions dominated. We processed the NIS data by applying the standard corrections for the bias, flat-field, cosmic rays, and 2″ slit burn-in, and by applying the Del Zanna et al. (2001) radiometric calibration. We then, with custom-written software, created mosaics of the nine rasters, by checking the alignment and by averaging the strips where overlap between successive rasters is present (Fig. 7). Since we are interested in the properties of the quiet-Sun radiances, we did not

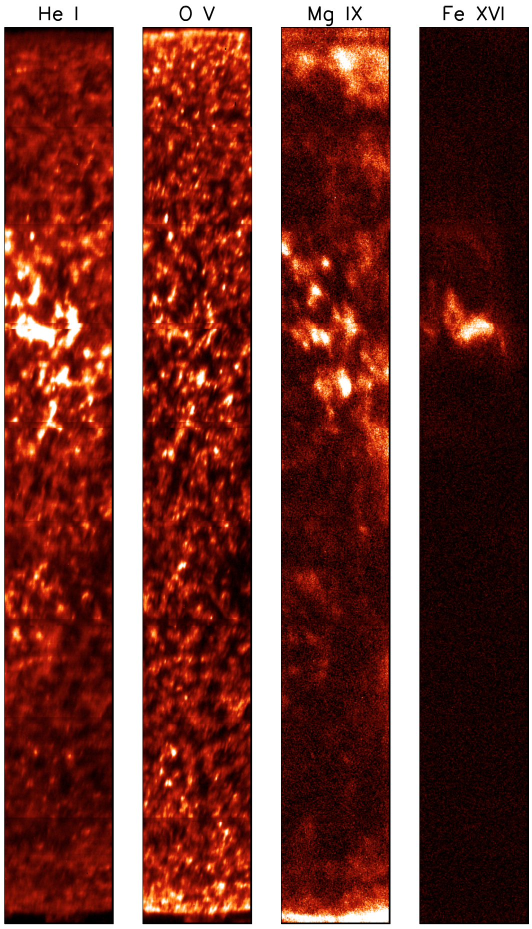

Fig. 7. Mosaics of NIS radiances in a few spectral lines (He I, O V, Mg IX, Fe XVI) observed with the SYNOP programme along a strip centred on the meridian.

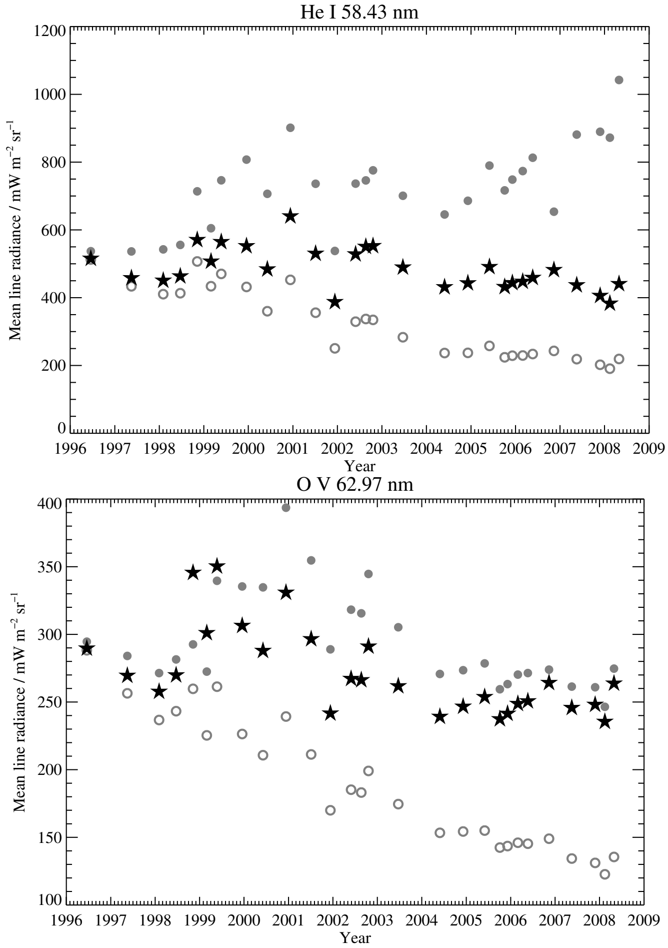

Fig. 8. Radiances of He I (*top*), O V (*bottom*) with and without the correction for gain depression. Open circles are radiances without corrections. Filled circles are the data with the "standard" correction currently available, while starred symbols indicate radiances with the correction proposed here.

consider data beyond 0.8 $R_\odot$, thus removing limb-brightening effects and, above all, avoiding the polar regions, which, especially during the minimum, are severely affected by the presence of coronal holes. From these mosaics, histograms of radiances were derived for each of the lines in the study.

We would like to point out that this is the first time that a study of radiance distributions along a cycle has been possible. At the low temperatures for formation of He I, O V, these distributions appear remarkably stable over quiet regions and are represented well by a log-normal distribution, a finding consistent with earlier studies (Wilhelm et al. 1998; Pauluhn et al. 2000).

To evaluate the variability with time of the centre of the log-normal distribution, we chose to estimate the "mode", or the peak of the radiance distribution in the CDS rasters away from the poles, via a Gaussian fit of the core of the distribution (which also provides an estimate of its width). We found this statistical estimate to be less sensitive than the mean or the median to the distortion of the distribution due to active regions (on the higher-radiance side) or to the occasional equatorial coronal hole (on the lower-radiance side). Figure 8 therefore shows estimates of the "quiet-Sun mean radiance": the effect of possible active regions or equatorial coronal holes crossing the meridian is small but possibly not negligible for the case of the O V line (cf. Fig. 8). As a result, there should be little or no influence on those radiances from solar cycle variations (except, of course, from possible, "intrinsic" variations in the quiet Sun itself.) Ignoring the drop in NIS responsivity would produce a marked drop in mean quiet-Sun radiances with time (open circles in Fig. 8). The "standard" correction currently available for this effects, while adequate for the O V line, would however result in a steady increase in He I radiances (filled circles). The correction we derived *independently* of NIMCP data (Sect. 2.2) does instead produce radiances in the current minimum consistent with the previous one (starred symbols in Fig. 8).

The differences between our long-term corrections and the standard ones are significant, not only for the later years, but also earlier on. The standard correction applied in version 4 increased the responsivity at 58.435 nm by about 15%, while we found a factor of only about 6%. We recall that the Del Zanna et al. (2001) responsivities were obtained from observations in 1997 without application of any long-term correction. We have therefore taken those values and applied the present corrections. These "scaled" responsivities are shown in Fig. 9, together with those of the "standard" CDS radiometric calibration version 4. The "scaled" responsivities are at most wavelengths within 20% of the standard ones.

3. NIS irradiances (USUN) compared to those from the EVE prototype

On April 14, 2008, the prototype of the SDO EVE instrument was launched on board a rocket (Chamberlin et al. 2009) and produced an excellent EUV spectrum that we used as a final

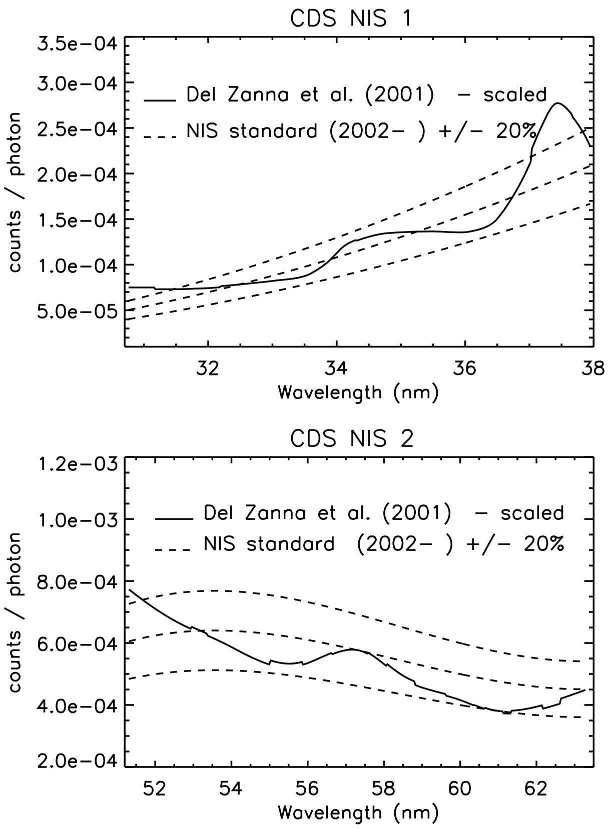

Fig. 9. CDS responsivities for both NIS 1 (*top*) and NIS 2 (*bottom*). The "scaled" (see text) values of Del Zanna et al. (2001) are shown, together with those of the 'standard' CDS radiometric calibration version 4 (dashed lines), and the same scaled by ±20%.

check on the NIS calibration by obtaining EUV irradiances from the USUN study. The SDO EVE instrument includes two spectrographs and multiple photometers for measuring the solar EUV irradiance from 0.1 nm to 122 nm (Woods et al. 2006). The EVE spectra are from the Multiple EUV Grating Spectrographs (MEGS) and have 0.1 nm spectral resolution. The MEGS A channel is a grazing incidence spectrograph for the 5–38 nm range, and the MEGS B channel is a double-pass normal incidence spectrograph for the 35–105 nm range.

To provide the solar EUV irradiance measurements at a high absolute accuracy (<20% relative uncertainties), a thorough calibration of all EVE channels was performed at the National Institute for Standards and Technology (NIST) Synchrotron Ultraviolet Radiation Facility (SURF III) in Gaithersburg, MD. The prototype EVE was illuminated directly by the primary standard radiation SURF source that has relative uncertainties of <0.2% (Arp et al. 2000). The details of the radiometric calibration technique and pre-flight results are presented in Chamberlin et al. (2007). A post-flight radiometric calibration at NIST has recently been carried out (Hock et al. 2009). We use this latest calibration.

The CDS USUN study consists of 69 rasters covering the whole Sun (with some off-limb coverage). The movement of the slit is "sparse" in the sense that the 4″ slit is moved in larger steps than its width. The total radiance of the Sun is therefore subsampled by about a factor of 6. Exposures are also binned on board along the slit, to increase the count rates and reduce the telemetry load. The NIS rasters do not observe the whole off-limb corona to great distances. As part of the analysis work in preparation for a follow-up paper, we also constructed mosaics of the NIS radiances and studied the off-limb behaviour of all the lines in the NIS spectra, to estimate the off-limb contribution that was not observed. For lines formed at chromosphere-TR temperatures, such as the majority of lines in the NIS 2 channel, the corresponding contribution is usually less than 1%.

No NIS full-Sun observations during the EVE prototype rocket flight were scheduled, so a direct co-temporal comparison is impossible. However, fortunately, the level of solar activity has been extremely low and a "featureless" Sun was typical for most of 2008. We did a preliminary analysis of many NIS full-Sun observations, and indeed found that spectral irradiances have been very constant in 2008. In particular, we processed the NIS full-Sun NIS irradiances obtained before (March 17, 2008) and after (May 26, 2008) the April 14, 2008 rocket flight and found no significant differences in the irradiances of all the lines. For the following, we only consider the spectra of March 17, 2008.

We processed USUN data as described in Sect. 2.1, except that, because the standard *SolarSoft* software does not correctly take data binning into account in this case, we used specially-written software for detecting and removing cosmic rays hits. We then obtained the radiances in all the lines, and constructed a mosaic of the rasters to check for pointing accuracy. We then linearly interpolated the spectra in the spatial domain, and then summed them. We then applied the Del Zanna et al. (2001) radiometric calibration. Finally, we applied the wavelength-dependent long-term corrections for the drop in responsivity. The resulting spectra are shown in Fig. 10 alongside the spectrum from the EVE prototype (red line). The NIS scattered light has been removed by subtracting a fixed amount for each channel. Indeed, the scattered light does not appear to have any significant wavelength dependence in the raw spectra, with the exception of the lower wavelengths of the NIS 1 channel. The large increase in the NIS 1 spectrum at lower wavelengths is mostly due to a residual scattered light component which is weak in the observed spectra, but is largely enhanced because of the low responsivity at short wavelengths (cf. Fig. 9)

The overall agreement between the NIS and EVE prototype spectra is excellent. In the NIS 2 channel, the spectral resolution of the EVE prototype is slightly lower, but all the main lines observed by NIS are also seen there. The He II 30.4 nm line observed in second order with NIS is not present in the EVE prototype spectrum. However this line, blended with Si XI, is observed in first order. The comparison between the NIS 1 and the EVE prototype is also very good. Here, the EVE-prototype spectral resolution is also lower, but the lines in the NIS 1 channel are so broad that measurements of integrated line radiances are very uncertain.

To provide a quantitative comparison, all the spectral lines have been fitted, those in the EVE prototype with Gaussian profiles, while those in the NIS spectra with the broadened profiles mentioned earlier. The largest uncertainty in the fit is the location of the background (the scattered light), in particular for the NIS 1 channel. The fitting in the NIS channels was done on the spectra in photon-events, where the scattered light component is more constant. Then, the various calibration factors were applied. The irradiances of those NIS lines which are blended in the EVE spectrum were summed for a direct comparison. Table 1 summarises the results. The first column provides the irradiances from the prototype-EVE, while the second column lists the NIS irradiances obtained by applying the Del Zanna (2001) scaled responsivities and the present long-term correction. It is clear that in the majority of cases, the NIS irradiances are within 30% of the prototype-EVE ones for both NIS 1 and NIS 2. Differences in some of the lines are partly due to the uncertainty in the NIS

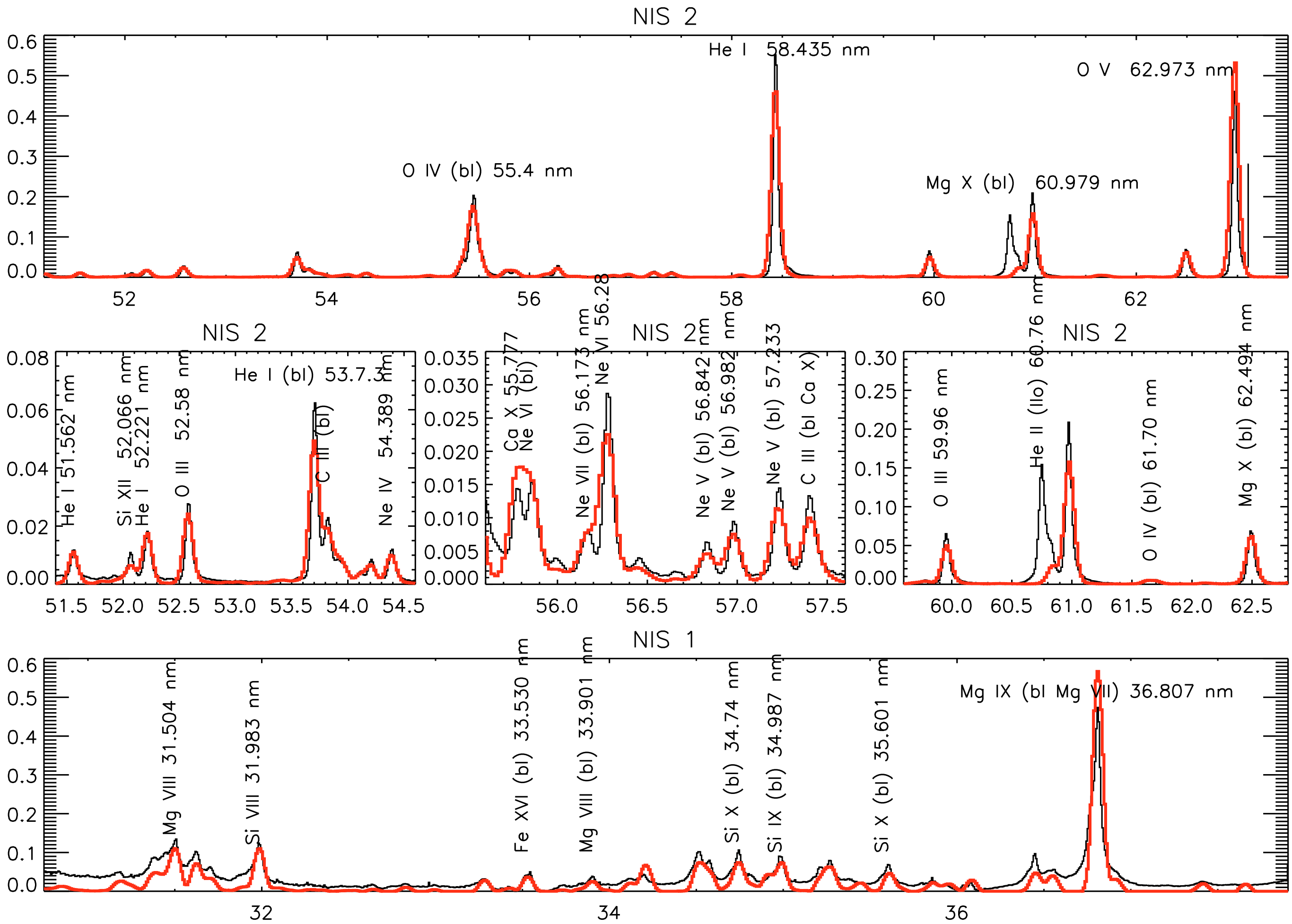

Fig. 10. Spectral irradiances from the NIS USUN spectra (black) and from the EVE prototype. The NIS data have been radiometrically calibrated with the Del Zanna et al. (2001) responsivities, and corrected for the present long-term correction. Ordinates are spectral irradiances E_λ/mW m^{-2} nm^{-1} and the abscissae wavelengths, λ/nm.

background subtraction and blending. A notable exception is the bright O V 63.0 nm line, where the irradiance from the rocket is about 1.6 times greater than the NIS measurement. The strong He I 58.4 nm is a factor of 1.3 larger. We would like to point out that our NIS measurements are in in very good agreement with the irradiances measured with the SOHO/SUMER instrument during the previous solar minimum in 1996 by Wilhelm et al. (1998). The SUMER irradiance in the He I 58.4 nm line ranged between 28.2 and 30.5, while the one for the O V 63.0 nm line ranged between 31.9 and 33.4 μW m^{-2}. Another notable exception is the irradiance of the He II 30.4 nm line. The overall agreement between NIS and EVE-prototype irradiances is however remarkable, considering the relative uncertainties in the responsivities (20% to 30% see Del Zanna et al. 2001) and the large (about a factor of 2) long-term corrections.

The third column shows the NIS irradiances obtained with the current (version 4) CDS responsivities and the present long-term corrections. We recall that the version 4 responsivities were obtained from the NIS/EGS comparison by applying the preliminary long-term corrections, so this combination is not self-consistent. It is, however, clear that the values in the second column are in better agreement at most wavelengths.

The fourth column presents the NIS irradiances obtained with the current version 4 of the CDS responsivities and the standard long-term corrections. In this case, large discrepancies are found. Some lines, such as the strongest He I 58.435 nm, have radiances that are too large, whilst many have values that are too low by almost a factor of 2. The main reason for these discrepancies are to be attributed to the incorrect treatement of the long-term correction discussed in Sect. 2.3. As an example, consider the weak Ar VII 58.575 nm transition. This line is close to the bright He I 58.435 nm and falls within the 90″ image of the latter. The previous method assumed that the main contribution to the long-term decrease in responsivity was caused by using the 90″ slit, so it applies too large a correction, which actually overestimates the irradiance. On the contrary, weaker lines such as the O III 60.0 nm had too small a long-term correction, producing a large underestimation of the irradiance.

4. Conclusions

The various NIS synoptic programmes have been very useful for the study of the long-term monitoring of the decrease in responsivity. By assuming that quiet Sun radiances in chromospheric and TR lines did not significantly change, we were able to obtain time- and wavelength-dependent long-term corrections to the NIS calibration. These corrections are significantly different from those previously available. We have found that the NIS instrument over 13 years has performed exceptionally well, with only a factor of about 2 overall decrease in responsivity from

Table 1. Irradiances in μW m^{-2}.

Spectral lines	λ (nm)	PEVE	*P*	*SN*	*S*
He II (bl Si XI)	30.400	309	663	502	395
Si VIII	31.983	8.2	11.7	12.5	7.6
Fe XVI (bl Mg VIII)	33.530	2.7	2.0	1.8	1.2
Mg VIII (bl)	33.901	1.9	1.8	1.8	1.1
Si X (bl)	34.750	5.6	6.3	6.8	4.3
Si IX (bl)	34.987	5.1	5.6	5.9	3.7
Si X (bl)	35.601	3.3	4.0	3.7	2.3
Mg IX (bl Mg VII)	36.800	42.	39.4	41.5	28.3
He I	51.562	1.2	1.0	1.3	0.87
Si XII	52.066	0.67	0.82	0.93	0.70
He I (bl)	52.221	1.9	1.5	1.7	1.3
O III	52.600	2.6	2.2	2.3	1.9
He I (bl)	53.703	5.2	4.9	4.6	4.0
Ne IV	54.207	0.66	0.51	0.46	0.34
Ne IV (sbl)	54.400	1.1	0.84	0.74	0.52
O IV (sbl)	55.450	26.4	25.4	21.6	20.8
Ne VI (2) (bl)	56.280	2.3	2.1	1.9	1.5
Ne V (2)	56.982	0.80	0.62	0.61	0.44
Ne V (3)	57.233	1.2	1.1	1.1	0.81
C III (bl Ca X)	57.420	1.1	1.0	1.0	0.75
He I	58.400	48.	36.	33.	78.
Ar VII	58.575	0.89	0.60	0.55	1.3
O III	60.000	5.2	4.8	4.0	3.0
Mg X (bl O IV)	61.000	16.	14.3	11.5	9.6
Mg X (bl)	62.500	6.6	5.8	5.1	3.9
O V	63.000	56.	35.	33.	35.

Notes. PEVE are the irradiances from the prototype-EVE, Apr 14, 2008. P are the irradiances from the full-Sun NIS observation of Mar 17, 2008, obtained with the Del Zanna (2001) scaled responsivities and the present long-term corrections; SN are the NIS irradiances of the same observation obtained with the current standard CDS responsivities (version 4, 2002) and the present long-term corrections; S are the same NIS irradiances obtained with the current standard CDS responsivities (version 4, 2002) and the standard long-term corrections.

1996 to 2009 in both channels. The NIS 2 channel is still providing excellent spectra, however the NIS 1 suffered badly during the period of SOHO loss. Future instruments such as the planned spectrometer for Solar Orbiter should have MCPs, so it is reassuring to see a good performance over such a long time.

A direct calibration of the NIS 1 channel is presented in a recent study by Wang et al. (2010). NIS 1 radiances were compared to those measured by the Extreme-Ultraviolet Normal-Incidence Spectrograph (EUNIS) during a sounding rocket flight on April 12, 2006. The EUNIS instrument was radiometrically calibrated on the ground at RAL, with the same facilities used for the SOHO CDS instrument. With the exception of a few of the strongest lines, an overall decrease in NIS 1 responsivity by a factor of 1.7 ± 0.2 was found. The standard version 4 responsivities and the NIS "standard" long-term corrections were applied by Wang et al. (2010). Their result is in very good agreement with our long-term corrections, so it confirms that the previous NIS "standard" corrections are inaccurate. In fact, using the present long-term corrections we predict an additional decrease by a factor of 1.5–1.6 across the NIS 1 channel.

We found good agreement (to within 30%) between the SDO EVE prototype irradiances and those from NIS, once our long-term corrections are applied to the NIS data. The EVE-prototype irradiances for the He II 30.4 nm, He I 58.4 nm, and O V 63.0 nm lines are significantly different from most previous measurements (sounding rockets or satellites dating back to the 1960's), as will be discussed in a follow-up paper. Work is in progress to understand the reasons for these discrepancies. The present work and the EVE-prototype results have prompted a re-calibration of the TIMED SEE data products (version 10) which is now available (since July 2009). Detailed comparisons with NIS irradiances will be performed in a follow-up paper. Additional direct cross-calibrations between the EVE MEGS instrument and the CDS NIS will be possible in 2010 after the launch of SDO.

We believe that providing a time-dependent absolute radiometric calibration for NIS, which compares so well to the excellent spectrum from SDO EVE prototype, after a period of 13 years of operation, is a considerable achievement. Our long-term corrections will be made available within the CDS processing software. A routine to return the scaled Del Zanna et al. (2001) responsivities will also be made available via *SolarSoft*.

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We thank the CDS team and the PI in particular for their interest to include the calibration presented in this study in the CDS processing software distributed through *SolarSoft*. CDS was built and operated by a consortium led by the Rutherford Appleton Laboratory (RAL), which includes UCL/Mullard Space Science Laboratory, NASA/ Goddard Space Flight Center, Max Planck Institute for Extraterrestrial Physics, Garching, and Oslo University. SOHO is a mission of international cooperation between ESA and NASA. The results obtained here could not have been achieved without the efforts of the operation and scientific staff, which successfully ran the CDS instrument, in large part at STFC/RAL (UK) and NASA/GSFC (US).
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Appendix A: Brief overview of the NIS calibration history

A pre-launch calibration of the flight CDS instrument was performed at the RAL in March 1994, using an EUV source that was previously calibrated against the BESSY synchroton beam. The first results were published in Bromage et al. (1996). The final revised results were later published in Lang et al. (2000). Only measurements at a few wavelengths were performed on the ground. For NIS 2, only measurements around three wavelengths were available. They showed significant discrepancies with the expected responsivities, based on theoretical calculations. Responsivities that follow the expected trends in wavelengths, but scaled to the measured values, were adopted. For NIS 1, measurements at 4 wavelengths were performed. Again, significant discrepancies with the expected responsivities were present, and the calculated wavelength-dependence was adopted. One measurement for the NIS 2 in second order was also provided, at 60.8 nm.

C.D. Pike (RAL) and H.E. Mason (University of Cambridge) used in-flight measurements to perform a preliminary correction to the ground calibration, in what became the NIS calibration version 1. The NIS responsivities were found by various authors to be too low. Landi et al. (1997) did not measure it, but proposed a factor between 2.5 and 5.

A sounding rocket flight launched in May 15 1997 carried an EGS spectrometer that had been calibrated at the National Institute for Standards and Technology (NIST) Synchrotron Ultraviolet Radiation Facility (SURF) in Gaithersburg, MD, with a relative uncertainty of 20% at the NIS 1 wavelengths and 12% for the NIS 2 channel. The spectrum had a coarse resolution (about 0.5 nm) compared to NIS (0.05 nm), and single emission lines were not resolved. A few broad blends were visible at the

NIS 2 wavelengths, while in the NIS 1 channel only the blend at 36.8 nm was observed.

On the same day, NIS performed a scan of the whole Sun with the 4″ slit, and the NIS "study" USUN_6. To reduce telemetry, the study was designed to rebin the spectra along the slit so only one pixel per exposure was returned to ground. The drawbacks of this procedure were the difficulty in removing cosmic ray hits and the much reduced spatial information, which did not allow an accurate estimate of the line irradiances from the radiance measurements.

Despite the various limitations, the EGS/NIS comparison provided the first (and only) direct in-flight calibration of the NIS instrument, and it was the basis for the version 2 of the standard NIS calibration. Details can be found in Brekke et al. (2000). The comparison of the strongest line, the He I 58.4 nm, provided a responsivity of $(4.75 \pm 0.4) \times 10^{-4}$ events/photon, in good agreement with the pre-flight measurement (not the original one, but the one revised by Lang et al. 2000). With regard to the other wavelengths, the results of Brekke et al. (2000) did not agree with either the ground calibration measurements or the theoretical predictions. Reliable measurements were not possible for the 59 nm to 61 nm region and at wavelengths below 53 nm.

On the other hand, the EGS/NIS comparison confirmed that at least at 36.8 nm the responsivity measured on the ground $[(1.86 \pm 0.5) \times 10^{-4}$ events/photon] was almost a factor of 3 lower than the in-flight one $[(6.77 \pm 1.7) \times 10^{-5}$ events/photon]. This large discrepancy was later attributed to undetected misalignment during the NIS 1 laboratory calibration. For the version 2 of the standard NIS 1 calibration, the theoretical curve was adopted and scaled to the value measured at 36.8 nm.

In 1997, the SERTS sounding rocket was launched. It carried a spectrometer with similar characteristics to the NIS and covered the spectral region from 31.0 nm to 35.5 nm. A comparison with near-simultaneous NIS radiance measurements was performed (Thomas et al. 1999; Thomas 2002). The comparison provided relative responsivities at the various NIS 1 wavelengths and was adopted to adjust the NIS calibration (still keeping as a reference the responsivity obtained from the EGS rocket at 36.8 nm) in what became version 3.

As pointed out by Del Zanna et al. (2001), an inconsistency in the SERTS-97/NIS comparison is present between the responsivities at wavelengths were lines formed at high and low temperatures were located. This was probably caused by a misalignment between the two instruments, which observed (not strictly simultaneously) an active region, a target not suitable for cross-calibration purposes. The SERTS rocket also observed the He II 30.4 nm resonance line, and provided a responsivity for the NIS 2 in second order at 60.8 nm of $(1.68 \pm 0.25) \times 10^{-5}$ events/photon, in excellent agreement with the value obtained from the EGS rocket.

Later, following the assumption that the use of the wide 90″ slit was the main cause of the long-term decrease in responsivity, preliminary corrections were implemented in the calibration software and used to analyse the EGS/NIS and SERTS/NIS comparisons again. This resulted in a general increase in the responsivities to 5.4×10^{-4} events/photon for the He I 58.4 nm line, and 1.86×10^{-5} events/photon for the He II 30.4 nm line. This formed the basis of the latest (version 4) CDS standard calibration, released on May 21, 2002.

One of us (GDZ) had done a full inter-calibration of all the 9 spectral regions (first and second order) of the NIS and GIS, using many observations in 1997 of different regions of the Sun as "calibration source". The relative responsivity at different wavelengths was obtained by comparing observed line ratios with theoretical and well-known (from previous, well-calibrated observations) observed values. Full details were presented in Del Zanna (1999), with a summary in Del Zanna et al. (2001). The responsivities were all relative to a single value, the responsivity at the He I 58.4 nm line. The value $(4.75 \pm 0.4) \times 10^{-4}$ events/photon obtained by Brekke et al. (2000) was adopted. The NIS 1 and all the GIS responsivities were found to be greater (by factors ranging from 1.5 to 3) than the pre-flight measurements. No corrections for long-term effects were introduced at that time.

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