Radiometric calibration tracking of the vacuum-ultraviolet spectrometer SUMER during the first year of the SOHO mission

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Detailed radiometric calibration tracking of the vacuum-ultraviolet spectrometer SUMER (from solar ultraviolet measurements of emitted radiation) was performed during the first year of the Solar and Heliospheric Observatory (SOHO) mission and will continue. In view of the flight history of many previous solar UV instruments, the stability of calibration of the extreme-ultraviolet instruments on SOHO has been a major concern. Results obtained during the first year of operation show that excellent radiometric stability has been achieved with SUMER. These results were accomplished by stringent cleanliness and contamination-control procedures during all phases of the project. We describe the strategy and results of the in-flight calibration tracking program performed with SUMER. © 1998 Optical Society of America

OCIS codes: 300.6540, 120.5630.

1. Introduction

With the Solar and Heliospheric Observatory (SOHO), an observation platform of the European Space Agency and the National Aeronautics and Space Administration was launched in December 1995. Among the 12 scientific instruments aboard, the solar ultraviolet measurements of emitted radiation instrument,[1] SUMER, is a VUV telescope and spectrometer that measures emission from the solar atmosphere with high spectral and spatial resolution. Within its wide wavelength range from 46.5 to 161.0 nm the instrument can map any part of the solar disk and the corona up to two solar radii and can provide spatially and spectrally highly resolved full Sun images.

To facilitate measurements of absolute radiant flux of solar emission lines, the spectral sensitivity of the instrument was calibrated in the laboratory[2] approximately a year before the launch of the SOHO spacecraft. Most previous solar VUV instruments suffered from sensitivity losses during their operation under solar-UV irradiation.[3–7] Consequently the stability of our calibration was a concern. To avoid degradation of the sensitivity of the instrument and to keep the laboratory calibration valid during operation, a comprehensive cleanliness-control program was implemented from the beginning of the project.[8] This program included many efforts not only in the design phase but also during assembly and testing. However, the effectiveness of all these measures would show only after extended operation in space. Based on laboratory studies of contamination of optical surfaces under solar irradiation, contamination budget requirements were established at the beginning of the project. Three possible sources of contamination were expected to contribute significantly to the degradation of optical surfaces in space: UV radiation, solar wind particles, and outgassing organic condensables. However, the combined effects of solar irradiation and organic contamination were considered to constitute the major process that leads to degraded optical performance: The deposition of organic contaminants is dramatically enhanced by chemical activation induced by solar radiation (solar wind and VUV) and subsequent po-

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Received 8 September 1997; revised manuscript received 18 November 1997.

0003-6935/98/132646-07$15.00/0

lymerization.[9] As a result the activated material is irreversibly deposited. With a design goal of less than 15% reflectivity loss of each optical surface, a maximum layer thickness of 0.1 $\mu g/cm^2$ was found to be the acceptable limit of contamination. Assuming that all outgassing organic species from the materials used in the optical part of the instrument could ultimately be polymerized upon the optical surfaces exposed to solar radiation, such a low contamination level could be achieved only by extremely careful material selection and cleaning processes. In addition, special design features such as an openable aperture door and an electrostatic solar wind deflector were implemented to reduce the contamination risk during ground and launch activities as well as in the operational phase.

A strategy was developed to conserve the radiometric calibration during ground and launch activities and to track stability during the mission. Without any calibration source aboard, various methods had to be employed to track the responsivity of the instrument during flight by using the Sun and bright UV stars as radiation sources. The strategy used to achieve a stable calibration was described previously.[10] Here we present results from the calibration tracking performed regularly during the first year of operation. The results presented show that the calibration during this time has not changed. In parallel, refinements of the laboratory calibration under operational conditions were performed.[11]

2. Laboratory Calibration and Its Refinement on the SOHO

The radiometric calibration performed before flight of the SOHO was described in detail in a previous publication.[2] In brief, the radiometric sensitivity of the SUMER instrument was calibrated by use of a hollow-cathode discharge source as a transfer standard, which was calibrated against the Berlin Electron Storage Ring for Synchrotron Radiation, a primary radiometric source standard. Using the bright emission lines of inert gases of the source, we measured the sensitivity of the instrument at various wavelengths in the spectral range from 53.7 to 147.0 nm. Both detectors (detector A and detector B) had to be calibrated independently. Each detector has a photocathode of bare microchannel plate on two sides and a potassium bromide (KBr) coating in the center part of the active area. Thus for each emission line of the source the calibration was performed on three positions of the photocathode of each detector. An average was taken over a large part of the detector's active surface to avoid the well-known small-scale nonuniformities of microchannel plate detectors. Despite fairly good coverage throughout most of the spectral range of the instrument, significant gaps remained in the sensitivity curve, particularly near 80 nm and at the long-wavelength side, because of the lack of emission lines from the inert gases. For most of these gaps, estimates could be produced during flight on the basis of star observations or measurements of solar emission lines with known intensity ratios, and a spectral sensitivity curve for detector A could be obtained.[11] When the effect of flux-limiting apertures and diffraction inside the instrument are taken into account, the relative uncertainty of radiometric measurements with SUMER is 15% (1σ) in the wavelength range of the laboratory calibration from 54 to 125 nm and 30% (1σ) for longer wavelengths.[2,11]

3. Tracking of Spectral Sensitivity during Flight

SOHO was launched on 2 December 1995. During the time between the ground calibration and the launch the SUMER instrument had been under a continuous purge with clean dry nitrogen. After launch the aperture door was partly opened in order to vent the optical housing without any VUV light entering the optical path. This situation was maintained for a period of approximately seven weeks during the transfer phase of SOHO to the inner Lagrange point (L1) and until the commissioning of the instrument was completed. The commissioning phase ended with the switch-on and first operation of the detectors. Only then was the aperture door opened for first VUV light on the telescope. Full spectra were recorded with the spectrometer using both detectors alternately, operated at the same parameter settings as during ground calibration. The measured line intensities of well-known lines from the solar spectrum[12] were found to be as expected, indicating that there was no substantial change in sensitivity during the period of more than a year between ground calibration and flight operation.

A. Flat-Field Exposures

During the following months of continuous operation of the instrument (interrupted only by short spacecraft maneuvers), regular long exposures of 3-h duration were taken at a wavelength of 88 nm (in the H I Lyman continuum) approximately every month for the purpose of flat-field illumination of the operational detector. For quasi-flat illumination of the detectors this wavelength range of the solar spectrum was chosen because here it is almost free of spectral line emissions, and with the grating focus mechanism in the most unfocused position any solar structure could be blurred over more than 20 pixels squared. As a result, features smaller than 16 × 16 pixels were chosen to be extracted from these data and attributed to the small-scale features of the detectors that can be used to correct subsequent images. The flat-field correction matrix was also kept onboard to correct images before data compression and transfer to the ground station.

The flat-field exposures were always taken under the same conditions at a position on the solar disk that was devoid of any activity and therefore represented quiet Sun conditions. The long integration time ensured deep exposure and a good average over the temporal variability of the emission from the viewed area. As a result, the total accumulated counts of these exposures should give a first time series of any possible sensitivity changes. The find-

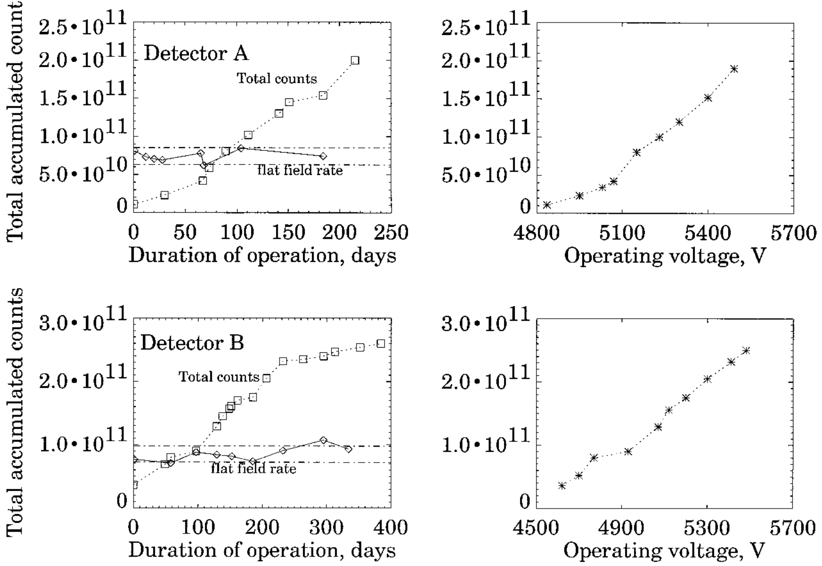

Fig. 1. History of detectors A and B with the count rates detected during flat-field integrations (in relative units dot–dash lines indicate levels of ±15% around mean) and the evolution of total accumulated counts during this period of almost two years (dashed curves). The right-hand panels show on the same scale the high voltage required for maintaining the detector gain, monitored by the pulse height distribution of the amplifier output, at the corresponding level of total counts.

ings were that no trend was seen that would indicate a degradation of the sensitivity.

During the first two months of operation a drop in the detector efficiency was noticed that was due to an amplification loss of the microchannel plates caused by irreversible changes in the plates. Raising the high voltage on the microchannel plates from time to time to compensate for the gain loss could restore the pulse height distribution whenever necessary to the same level as during the ground calibration. In this way the detector efficiency was kept at a constant level. We verified this result independently after seven months of operation of detector A (the high voltage had been raised in several steps from 4832 to 5500 V in the meantime) by comparing the sensitivity of detector A with that of detector B, which had not been used during the period after its initial operation during the commissioning phase. First, we verified that detector B was performing under the same conditions as during ground calibration; then a comparison of the two detectors revealed that the ratio of efficiencies was unchanged from the laboratory calibration, despite the different levels of the operating high voltages. Figure 1 summarizes for each detector the history of total accumulated counts during the time of operation (left-hand panels) and the high voltage used to maintain the operating gain level (right-hand panels) as a function of total accumulated counts. Overlaid on each left-hand panel is the flat-field counting rate (in relative units) during the flat-field integrations of 3 h each. The variation in the flat-field counts is within the limits of variability of the solar area seen during each measurement. No decrease of sensitivity can be inferred from these data. However, an increase in sensitivity or in radiant flux of less than 20% may be possible, as we confirm with further radiance measurements described below.

B. Radiance Measurements of the Quiet Sun

To track the stability of the spectral sensitivity of the SUMER instrument, regular observations of selected emission lines of the quiet Sun in or near the disk center have been performed since March 1996. These observations are part of the SOHO intercalibration programs aiming for cross calibrations between the spectroscopic instruments on SOHO.

The Coronal Diagnostic Spectrometer (CDS) on SOHO,[13] which is observing the Sun in the spectral range from 15 to 80 nm, extends the SUMER spectral range to shorter wavelengths, but the two instruments have a considerable overlap in their wavelength ranges. Because the CDS has followed a similar technique for its radiometric calibration before launch,[14] a SUMER–CDS cross calibration during flight has been considered important. For this purpose an observation program (SOHO–Intercal-1) was defined that scans the same area on the quiet solar disk by both instruments simultaneously and coregisters emission lines in the overlapping spectral region. SUMER selected four emission lines between 58.43 and 77.04 nm for this intercomparison (Table 1). Also included in the Intercal-1 observation program are two emission lines, at 123.88 and 124.20 nm, for additional cross calibration with the Ultraviolet Coronagraph Spectrometer,[15] which has an overlapping wavelength band with SUMER from 98.4 to 128.7 nm. The results of the interinstrument comparisons will be reported in a later publication in which the other SOHO instrument teams involved will participate. Here we use the data obtained to study the behavior of SUMER under operational conditions.

The measurements were performed with the SUMER standard slit of 1 × 300 arcsec^2 (1 arcsec = 715 km on the Sun). An area of the solar disk was

Table 1. Emission Lines and Exposure Parameters for the Intercal-1 Program

Line	Wavelength (nm)	Detector (Photocathode)	Order of Diffraction
He I[a]	58.433	A (Bare)	Second
		B (Bare)	Second
Mg X[a]	60.979	A (Bare)	Second
		B (Bare)	Second
Mg X[a]	62.494	A (Bare)	Second
		B (Bare)	Second
Ne VIII[a]	77.041	A (Bare)	Second
		B (Bare)	First
N V[b]	123.882	B (KBr)	First
Fe XII[b]	124.203	A (KBr)	First
		B (KBr)	First

[a] For cross calibration with the CDS.

[b] For cross calibration with the Ultraviolet Coronagraph Spectrometer.

scanned in 80 steps (step size, 0.76 arcsec) in an east–west direction, forming a solar image of 61 × 300 arcsec^2. To show contributions from weak lines nearby and the underlying continuum (both orders are superimposed), the spectral radiance of the selected emission lines averaged over the scan area is displayed in Fig. 2. The conversion from detector signal [counts pixel^{-1} s^{-1}] to spectral radiance [photons s^{-1} m^{-2} sr^{-1} nm^{-1}] was performed with the data in Ref. 11 (cf. the Website http://sohowww.nascom.nasa.gov/descriptions/experiments/sumer/radcal.html).

From these measurements we deduced the mean solar radiance of the emission lines in the observed area by integrating the line profile. The He I (58.433-nm), Ne VIII (77.041-nm), and N V (123.882-nm) emission lines are so isolated that their line profiles can be summed in the spectral dimension after the background signal has been subtracted. The background corrections for these three lines were made individually for every Intercal-1 spectrum. Typical numbers for the required corrections are He I (58.433-nm) background correction of 8% for a 0.069-nm spectral window, Ne VIII (77.041-nm) background correction of 12% for a 0.065-nm spectral window, and N V (123.882-nm) background correction 29% for a 0.134-nm spectral window. For the He I line, detected in second order, an additional deduction of 1.2% was necessary to account for first-order contributions from N I lines. The profiles of the other three lines had to be treated with a Gaussian fit routine, whereas we performed the background subtraction by fitting a polynomial of second degree to the background signal. Because the detector event rate stays clearly below 10 counts s^{-1} pixel^{-1} for all six emission lines, no correction for local gain depression of the microchannel plates had to be applied to the data. The results are summarized in Fig. 3. Here we show the radiances measured for each line during more than a year of operation. In the bottom panel of Fig. 3 the actual dates of measurements are indicated. Variations of the radiances of as much as 30% in the observed quiet Sun emission lines are larger than statistical errors. As the data for one measurement sometimes vary in opposite directions for different emission lines, which are formed at different local heights and temperatures, we account these variations as being due to real local changes in the solar atmosphere. No loss in sensitivity of the instrument since March 1996 can be deduced from these measurements. A linear regression was made for all the data from ≈15 months. For all lines (except Fe XII we find a slight increase Whether this trend is instrumental or is caused by the changes of solar radiance as a consequence of the increasing solar activity cycle cannot be answered at this stage.

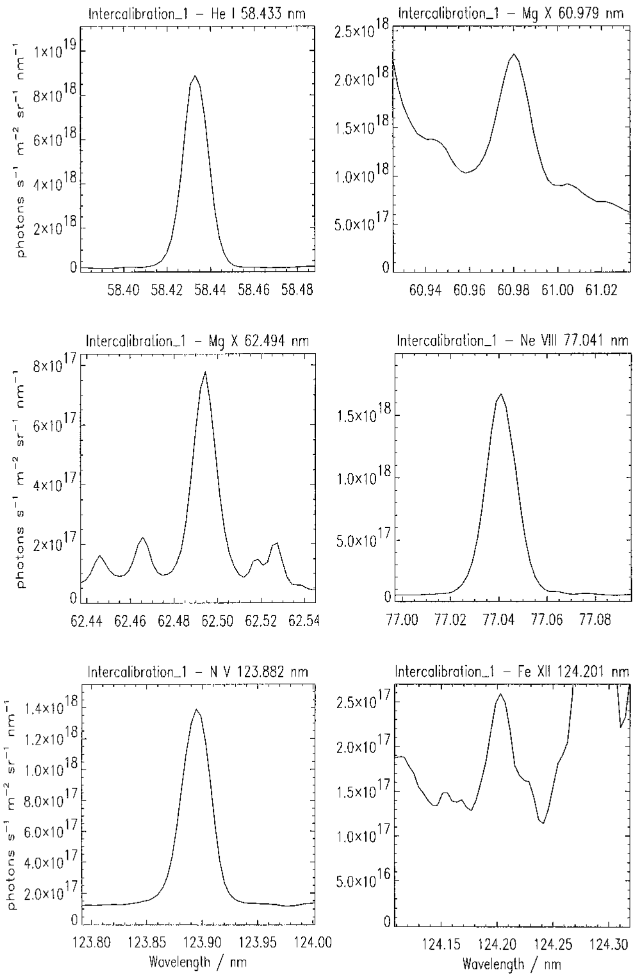

Fig. 2. Spectral profiles of lines used for calibration tracking measurements. For some of the lines substantial background corrections are necessary and contributions from neighboring lines have to be accounted for.

4. Comparison with Solar Irradiance Measurements

We compared our spatially resolved radiometric data with irradiance data from the full solar disk measured by other instruments. In comparing results from spatially resolved observations with full disk observations one has to be extremely careful. Contributions from different features on the disk, such as active regions and coronal holes, and center-to-limb

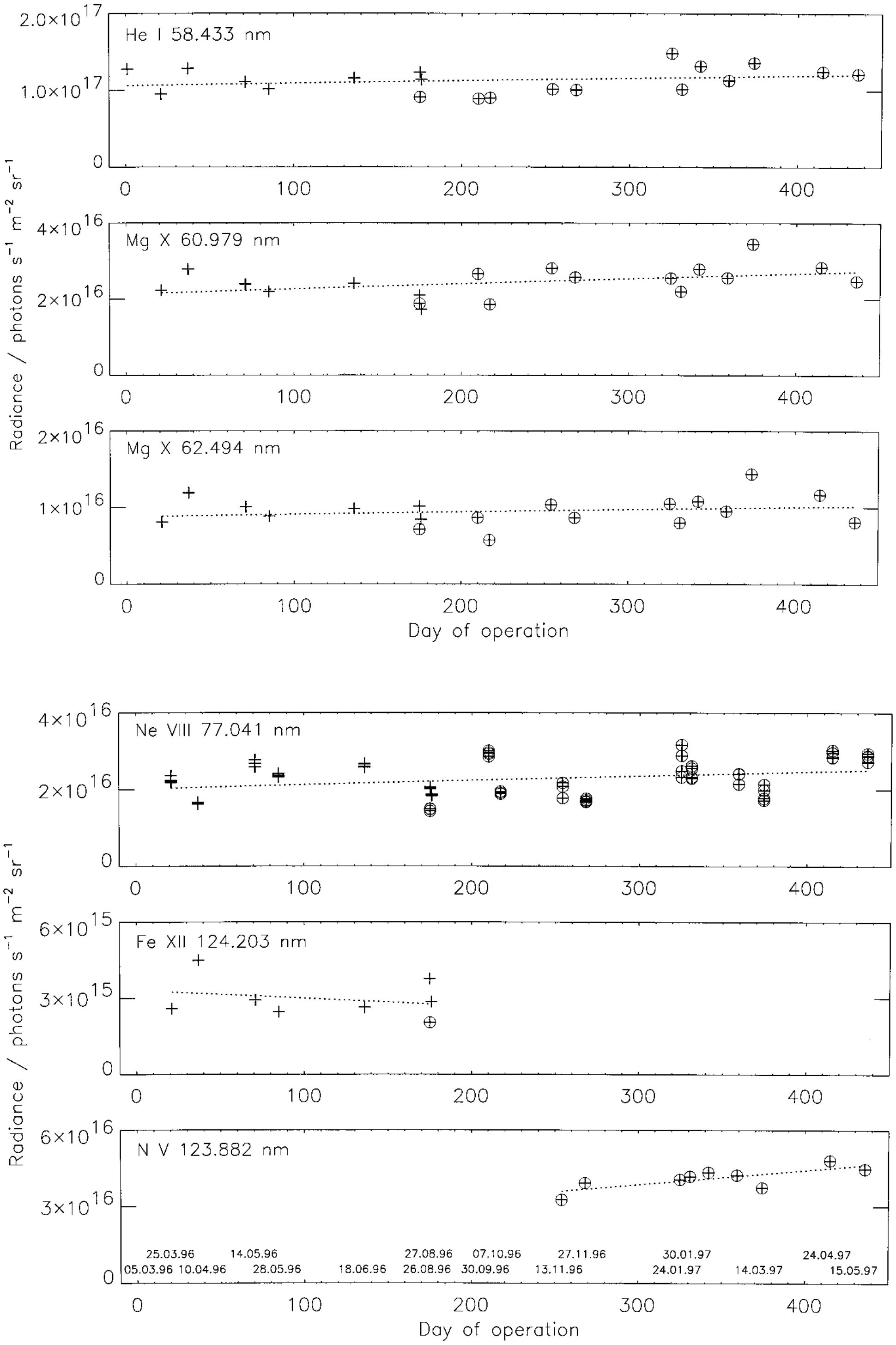

Fig. 3. Radiances of the emission lines of He I (58.433 nm), Mg X (60.979 and 62.494 nm), Ne VIII (77.041 nm), Fe XII (124.203 nm), and N V (123.882 nm), measured during several calibration runs between 5 March 1996 and 15 May 1997. Each data point is an average over an area of 60 × 300 arcsec^2 in a quiet area of the solar disk. Different symbols are used for data of detectors A and B (with circles). Note that measurement of Fe XII was abandoned in favor of measuring the brighter N V line. The dates of the measurements are indicated in the lowest panel.

variations (limb brightening) are not resolved in full disk measurements. Furthermore, the spectral resolution of the observations to be compared must be adequate to ensure a unique identification of the spectral features considered.

The Solar–Stellar Irradiance Comparison Experiment (SOLSTICE) on the Upper Atmospheric Research Satellite is a three-channel UV spectrometer measuring solar and stellar fluxes from 115 to 420 nm with a spectral resolution of 0.1 to 0.2 nm for solar observations.[16] SOLSTICE was radiometrically calibrated at the Synchrotron Ultraviolet Radiation Facility of the National Institute of Standards and Technology as an irradiance standard. During flight the stability of the instrument is monitored by repeated observations of the UV flux from standard stars.[17]

The EUV Grating Spectrograph (EGS) is another

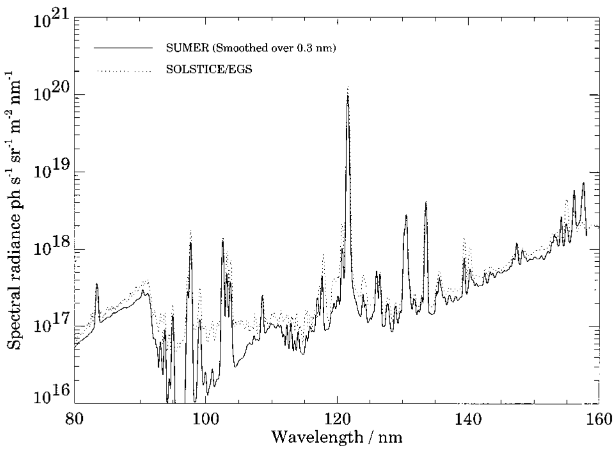

Fig. 4. Comparison of the radiance spectrum measured with SUMER in a quiet Sun location on the solar disk with the full disk integrated irradiance measurements of SOLSTICE–EGS.

full disk irradiance monitor that has been launched on sounding rockets.[18,19] The instrument covers the spectral range from 30 to 119 nm with 0.3-nm spectral resolution (0.1 nm per detector anode). The EGS solar spectral irradiance data have a relative uncertainty of 6% to 10%. The radiometric calibration is also based on the Synchrotron Ultraviolet Radiation Facility as an irradiance standard.

In Fig. 4 we compare the entire SUMER spectrum measured on 12 August 1996 with the EUV–VUV irradiance observations obtained on 3 November 1994. We derived the latter by combining the EGS spectrum ($\lambda < 119$ nm) with observations from SOLSTICE ($\lambda > 119$ nm), both obtained on the same day.

The SOLSTICE–EGS full disk spectrum can be considered to be an average quiet Sun spectrum. We made the comparison between SUMER and the irradiance measurements by reducing the SOLSTICE–EGS irradiance values to the mean radiance of the solar disk and degrading the spectral resolution of the SUMER spectrum to match the spectral resolution of the irradiance measurements. We converted the irradiance values from flux at 1 AU to average radiance of the solar disk by using the expression

$$E(\lambda) = (\pi R^2/r^2)L(\lambda),$$

where R is the solar radius and $r = 1$ AU (the effect of using 1 AU instead of the actual distance between the Sun and Earth during the observations is less than 2.7%).

From independent evaluation of the full Sun images taken by SUMER the contributions from limb brightening, active regions, and coronal holes could be estimated for several emission lines of different formation temperatures. The correction for small active regions and coronal holes is not significant under quiet Sun conditions, except for lines of high formation temperature, which are present in the SUMER spectrum as second-order contributions. Correspondingly, we found the SUMER values higher than the SOLSTICE–EUV data, only where we have dominating second-order lines. We see from Fig. 4 that the measurements agree very well, and the irradiances given by the SOLSTICE measurements, which include the radiation from the solar limb and possible bright regions, are generally higher than the SUMER results. We should mention that actual peak intensities of spectral lines are approximately an order of magnitude higher when they are fully resolved as in the undegraded SUMER spectrum[20] than the intensities shown in this figure, where the spectral resolution has been artificially degraded.

The center-to-limb variation of the solar UV continuum longward of 140 nm has been studied by Brekke and Kjeldseth-Moe.[21] They found that the spectral variation of the ratio of the radiance at disk center to the average radiance of the entire disk does not depend strongly on the detailed center-to-limb variation. From the spatially resolved full Sun images of SUMER the center-to-limb variation was measured for some representative lines.[20] Most lines in the SUMER spectral range are optically thin and show substantial limb brightening, which for typical lines from the solar transition region leads to an average radiance of the solar disk of approximately twice the radiance at disk center. We therefore expect that the irradiance from the full Sun will be higher than from the quiet disk center for most of the lines observed in this spectral range. The large discrepancy seen in Fig. 4 between 93 and 110 nm, however, remains unexplained.

5. Summary and Outlook

The radiometric stability of the solar VUV spectrometer SUMER during the first year of continuous operation in space has been demonstrated. In particular, any degradation owing to combined effects of organic material outgassing and solar-UV irradiation of the normal-incidence mirrors has been avoided. For successful prevention of degradation a comprehensive cleanliness-control program was carried out during the project development period. The results presented here show that the cleanliness requirements have been met and justify the technical and financial efforts made related to the cleanliness issues. In regard to future solar VUV space missions a substantial leap has been accomplished toward instrumentation free of degradation caused by contamination. With a strategy of regular measurements of the instrument sensitivity from the beginning of in-orbit operations it was possible to transfer the laboratory calibration into the operational phase and track the radiometric responsivity over the elapsed operational period.

SOHO is a project of international cooperation between the European Space Agency and the National Aeronautics and Space Administration. The SUMER project is financially supported by the Deutsches Zentrum für Luft- und Raumfahrt, the Centre National d'Etudes Spatiales, the National Aeronautics and Space Administration, and the European Space Agency PRODEX program (Swiss contribution).

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