UARS SOLSTICE Data as a Calibration and Validation of GOME

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Abstract

The GOME instrument consists of a spectrometer and scan mechanism to provide spectral radiance measurements of the earth's atmosphere over the entire spectral range 240 to 790 nm. The photometric calibration of the instrument is accomplished with a separate calibration unit including both calibration lamps and a diffuser to direct solar radiation into the spectrometer. In this report we concentrate on a calibration activity using the solar irradiance as a well calibrated source of known illumination, and from the GOME instrument response we derive the sensitivity of the instrument and changes in the instrument response with time. As the "known" solar input we use daily observations of the SOLSTICE instrument on NASA's Upper Atmosphere Research Satellite (UARS). SOLSTICE covers the spectral range from 120 to 420 nm, and the overlap with GOME spectral range provides a calibration of channels 1 and 2. The 2σ absolute calibration of the SOLSTICE data is ±4%, a value that can be transferred to the GOME observations by direct comparison of the two data sets. In addition, the 2σ relative accuracy of the SOLSTICE data set is approximately ±2%, and helps to determine trends and changes in the GOME instrument response. The GOME/SOLSTICE comparison establishes characteristics of the GOME instrument in the solar irradiance configuration only, and additional and ancillary information on the solar diffuser and scan mirrors is also required to establish the calibration of GOME for radiance observations.

1. INTRODUCTION

The Global Ozone Monitoring Experiment (GOME) was launched onboard the ERS-2 spacecraft in April 1995. This instrument is a nadir-viewing spectrometer that observes solar radiation backscattered by the Earth's atmosphere and scattered from its surface. Because the input solar radiation is absorbed along its path through the atmosphere, the returned spectra recorded by GOME contain detailed information of the atmosphere's content of ozone, nitrogen dioxide, water vapor, as well as other trace gases. Knowledge of the solar radiation input is also usually required to establish the amount of absorption, although there are differencing techniques that to first order are independent of the incoming solar radiation because they use two or more wavelengths. In order to extract reliable quantitative information on the atmospheric constituents, we require precise knowledge of the sensitivity of the GOME instrument. Moreover, in order to detect changes in time of these atmospheric constituents, we will require an additional precise understanding of how the GOME instrument sensitivity has evolved and varied in time.

The GOME instrument can directly measure the Earth's radiance scattered into its spectrometer, or in an alternate mode, using a slightly different optical path, it can measure the solar irradiance arriving at the instrument. In both configurations, the optics of the spectrometer are the same, only a scanning mirror and diffuser are inserted for the direct solar measurement. In order to extract the desired geophysical unit of observed radiance, we must establish the efficiency of the instrument to transfer and convert the incoming radiation to a recorded instrument signal. This efficiency is determined in the pre-launch calibration, but then it needs to be validated once the GOME is operating on-orbit, and furthermore, it must be continually monitored as the mission proceeds. From a long history of space observations, there is every reason to believe that in time the GOME efficiency will change and, in fact, the efficiency will usually decrease with time. This aging process is likely a complicated combination of contamination of optical elements coupled with the exposure to radiation, especially very energetic ultraviolet radiation of the Sun. By limiting exposure and taking every precaution to avoid contamination, both in the preparation and testing of the instrument prior to launch and in the outgassing environment of the satellite on orbit, the instrument degradation can be minimized to perhaps only a few percent per year of operation.

In the research project described here, we use a priori information of the solar radiation to establish the GOME instrument response and to evaluate how this in-flight efficiency compares with the pre-launch calibration of the instrument. We are using the ultraviolet irradiance measurements of the SOLSTICE instrument, one of two UV irradiance instruments on the Upper Atmosphere

Research Satellite (UARS). These measurements extend back to the launch of UARS late in 1991 and are expected to continue for at least another three to five years. Therefore the SOLSTICE will provide a continuous data set for the cross-calibration of the GOME instrument. Although details of its optical design are quite different from the GOME design, the SOLSTICE is also a spectrometer with spectral coverage overlapping the GOME channel 1 and channel 2 and with comparable spectral resolution. The SOLSTICE measurements have their own inherent uncertainties with respect to both absolute calibration and with respect to drifts in the instrument response over time, and these factors are considered in this report. We rely on the independence of the two observations to gain an important insight into the validity of the measurements and our confidence in the respective calibration techniques, with special emphasis on an improved understanding of the GOME performance.

The SOLSTICE instrument is described below in Section 2. Its observations have been validated by comparison with the SUSIM instrument on UARS and with the SSBUV and SUSIM instruments on the first two ATLAS missions, and the resulting solar irradiance scale is believed to be accurate to ±4%. Section 3 discusses the GOME observations and compares channel 1 (240 to 295 nm) and 2 (290 to 405 nm) with the SOLSTICE measurements. We discuss three aspects of the comparison: the wavelength registration, the irradiance validation (differences in absolute calibration), and trends that can be established in the GOME instrument response. Finally, in Section 4 we give our conclusions and our recommendations for future activities.

2. OVERVIEW OF THE SOLSTICE MEASUREMENTS

The Solar Stellar Irradiance Comparison Experiment (SOLSTICE) is one of ten instruments on the Upper Atmosphere Research Satellite (UARS). The primary scientific objective for the SOLSTICE program is to make precise and accurate measurements of the solar spectral irradiance, over the spectral range 119 to 420 nm. Moreover, it has a goal of measuring solar variability over arbitrarily long time periods, for example, over the duration of the UARS mission that may exceed ten years. The requirement for absolute accuracy is on the order of ±10% (2-σ value), but the requirement for relative accuracy between any two measurements spaced throughout the UARS mission is ±2% (2-σ value). To achieve these goals the instrument response is determined from both preflight calibrations and from in-flight calibration and validation programs. The SOLSTICE has been designed with the unique capability of monitoring a number of bright blue stars (those with O and B spectral type) using the same optical elements and detectors employed for the solar observations. These stars, which vary by only small fractions of a percent over long time periods, provide a stable reference for deriving the SOLSTICE instrumental degradation rates.

A second instrument, the Solar Ultraviolet Irradiance Monitor (SUSIM) (Brueckner et al., 1993), is also aboard UARS measuring the solar UV irradiance with basically the same spectral coverage and resolution as SOLSTICE. However, SOLSTICE and SUSIM have quite different optical designs and, moreover, employ dramatically different in-flight calibration techniques.

The reader is referred to papers by Rottman et al. (1993), Woods et al. (1993), and Woods et al. (1996) for details of the SOLSTICE instrument design, measurement technique, calibrations, and validations. Briefly, SOLSTICE is a three channel grating spectrometer which uses the same optical elements for both the solar and stellar observations but uses interchangeable entrance apertures, bandpasses, and integration times to accommodate the 10^8 : 1 dynamic range between the solar and stellar irradiances. The three overlapping channels are the G channel from 119 to 190 nm ($\Delta\lambda$=0.1 nm), the F channel from 170 to 320 nm ($\Delta\lambda$=0.25 nm), and the N channel from 280 to 420 nm ($\Delta\lambda$=0.35 nm). Only the SOLSTICE F and N channel data are included here for comparisons with the GOME solar irradiances at wavelengths longward of 240 nm.

For the solar irradiances, the SOLSTICE data are corrected for scattered light, detector linearity, detector dark counts, detector gain changes, instrument sensitivity and degradation. The stellar irradiances undergo similar processing, but the degradation factors are treated as free parameters and are adjusted to make the mean stellar irradiance invariant in time. The resulting degradation factors are then the same ones applied to the solar data. The wavelength scale is referenced in vacuum wavelength units to high resolution solar spectra above 200 nm (Anderson and Hall, 1989; Kurucz, 1991) and to atomic or ionic transition levels below 200 nm (Sandlin et al., 1986; Kelly and Palumbo, 1973; Kelly, 1987). Each spectrum's wavelength scale is also adjusted to the SOLSTICE reference wavelength scale to account for small wavelength shifts related to temperature changes and to pointing offsets. The primary science requirement is to provide one full solar spectrum per calendar day, and to achieve this, the data processing algorithm combines typically 15 individual observations to form the single daily spectrum, adjusted to 1 AU. This daily SOLSTICE spectrum, called the Level 3BS product, is reported for each 1.0 nm interval (centered on the half nm) between 119 to 420 nm and is available from the NASA Goddard data center (its Web address is http://daac.gsfc.nasa.gov).

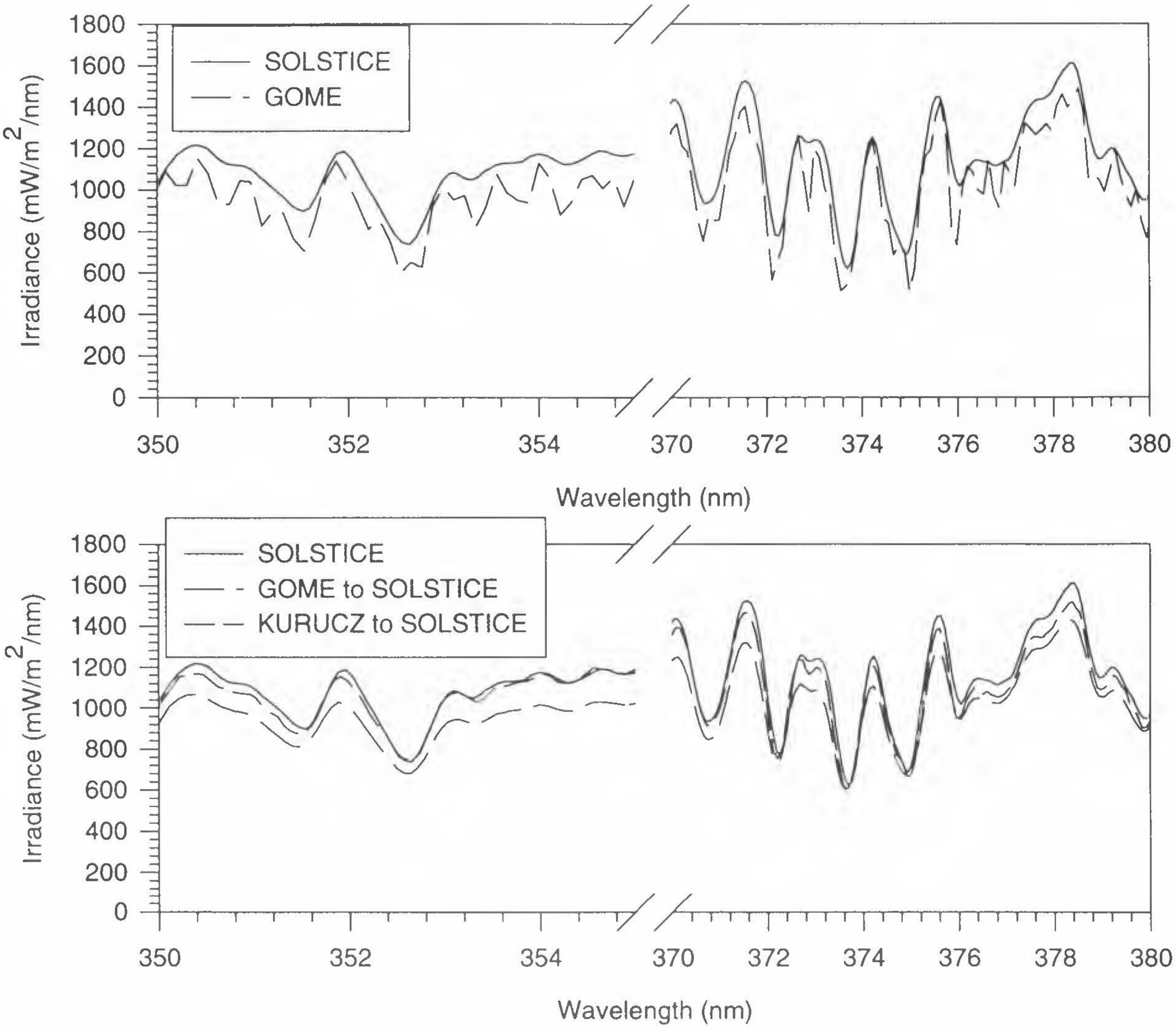

Figure 1. *(a) Two wavelength regions of SOLSTICE and GOME irradiance at instrumental resolution showing the differences in resolution. (b) SOLSTICE at instrumental resolution compare to GOME and high resolution ground based spectra convolved with the SOLSTICE effective bandpass.*

The validation of the SOLSTICE solar irradiances was a joint effort of four solar UV irradiance programs (Woods et al., 1996). The measurements of the solar ultraviolet spectral irradiance made by the two UARS solar instruments, SUSIM and SOLSTICE, are compared with same-day measurements by two other solar instruments on the Shuttle Atmospheric Laboratory for Applications and Science (ATLAS) missions, ATLAS SUSIM and Shuttle Solar Backscatter Ultraviolet (SSBUV) experiment. Measurements from the four instruments agree to better than the 2-σ uncertainty of any one instrument, which is ±5-10% for all wavelengths above 160 nm, as well as for strong emission features below 160 nm. Additionally, the long-term relative accuracy of the two UARS data sets is better than the original 2% goal, especially at wavelengths greater than 160 nm. This level of agreement is credited to accurate pre-flight calibrations coupled with comprehensive in-flight calibrations to track instrument degradation. Because the agreement of the SOLSTICE solar irradiance with the other three measurements is better than the SOLSTICE absolute accuracy of ±10%, the SOLSTICE uncertainty presented in this report (e.g. Section 3 and fig 2) is the SOLSTICE relative accuracy (~2%) plus the average of the differences between the four solar irradiance measurements from UARS and ATLAS (Woods et al., 1996).

3. GOME INSTRUMENT PERFORMANCE

The GOME instrument performs daily observation of the solar irradiance during its Sun Observation Timeline (SOT), a 42 seconds timeline inserted into the Normal Observation Timeline (NOT) when the satellite is close to the earth's north pole. Prior to launch the sensitivity of GOME was evaluated using radiance standards, namely 1000 Watt FEL lamps calibrated by NIST (ESA, 1995). Although carefully checked on the ground, in-flight validation of the solar irradiance is necessary to detect changes or drift in the response of the instrument. This is particularly important for solar irradiance measurements since they are performed using a diffuser plate and mirror inserted between the sun and the detector. Furthermore, changes in the response of the instrument are to be expected, especially early in the mission when the satellite has been put into orbit and first exposed in vacuum to highly energetic solar radiation. The diffuser and other optical elements will likely change during the satellite lifetime, and their performance will evolve with respect to preflight calibration. For these reasons, external and independent sources of solar irradiance are essential for monitoring of the in-flight performance. The SOLSTICE daily solar irradiance measurements provide an accurate and validated reference for this purpose.

Up to now, only limited GOME solar irradiance spectra have been provided by DLR and included in this work: July 22 to 25, August 24 to 27, September 1 to 3 and 14 to 17, October 4 to 7 and 29 to 31 and November 8 to 11. As far as possible, time coincident SOLSTICE irradiance spectra are retrieved from the NCAR database, and we have used the "level 3BS merged" high resolution products.

It is important to note that only SOLSTICE data up to September 1994 are fully validated and released. Data used in this work are preliminary and provisional. More specifically, new calibration parameters taking into account revised stellar pointing information are now being applied to the 1995 data.

3.1. Wavelength validation

Since July 22nd, all GOME wavelength values are reported in vacuum, as is the case for SOLSTICE wavelengths. Therefore there is no need to convert from one scale to another as was the case for the first two GOME spectra (30 May and 6 June).

The spectral resolution of GOME and SOLSTICE are somewhat different. Although the theoretical SOLSTICE resolution is 0.2 nm for channel F and N, the "effective" bandpasses are larger. The SOLSTICE spectrometer design (Monk-Gilleson) only permits a single wavelength to be in perfect focus and other wavelengths will have a slightly broader effective bandpass. This effect is about 10% over the spectral range if the best focus is in the center of the spectral range. If the best focus is not centered in the spectral range, then the effective bandpass becomes even larger. The effect is about 1.1 for the F channel ($\Delta\lambda$~0.25 nm) and 1.8 for the N channel ($\Delta\lambda$~0.35 nm). The differences between SOLSTICE and GOME resolution can be seen in Figure 1a where both irradiances are plotted at instrumental resolution for 22 July 1995. One can clearly identify in the GOME spectrum features missing in the SOLSTICE spectrum. Note that the displayed wavelength region correspond to channel N of SOLSTICE where the effective bandpass is the largest. Figure 1b depicts both GOME and high resolution ground based spectra (Kurucz et al, 1991) convolved with the SOLSTICE effective bandpass. The different features and structures now match very well between the two spectra.

3.2. Irradiance validation

The SOLSTICE irradiance are reported adjusted to one astronomical unit and GOME is adjusted accordingly using the formula:

$$I_0 = I\left(\frac{d}{d_0}\right)^2 \tag{1}$$

where

$$\begin{aligned}\left(\frac{d_0}{d}\right)^2 &= 1.000110 + 0.034221\cos\Gamma \\ &+ 0.00128\sin\Gamma + 0.000719\cos 2\Gamma \\ &+ 0.000077\sin 2\Gamma\end{aligned} \tag{2}$$

and $\begin{matrix}\Gamma = 2\pi(J-1)/365 \\ 1 \le J \le 365\end{matrix}$,d_0 correspond to 1 AU. Hence.

The procedure used to adjust both spectra to a common wavelength scale is the same that has been defined for the UARS/ATLAS irradiance comparison (Woods et al., 1996). Each spectrum is first interpolated to a common 0.025 nm scale.. The resulting spectrum is then convolved to a common 1 nm grid, centered at half nm, ranging from 240 to 420 nm using a triangular convolution kernel of 1 nm FWHM. This procedure removes many (but not all) of the discrepancies most notable near the strong absorption lines. The relative irradiance difference is defined as

$$\Delta(\lambda) = \left(\frac{I_{GOME}(\lambda)}{I_{SOLSTICE}(\lambda)} - 1\right) \tag{3}$$

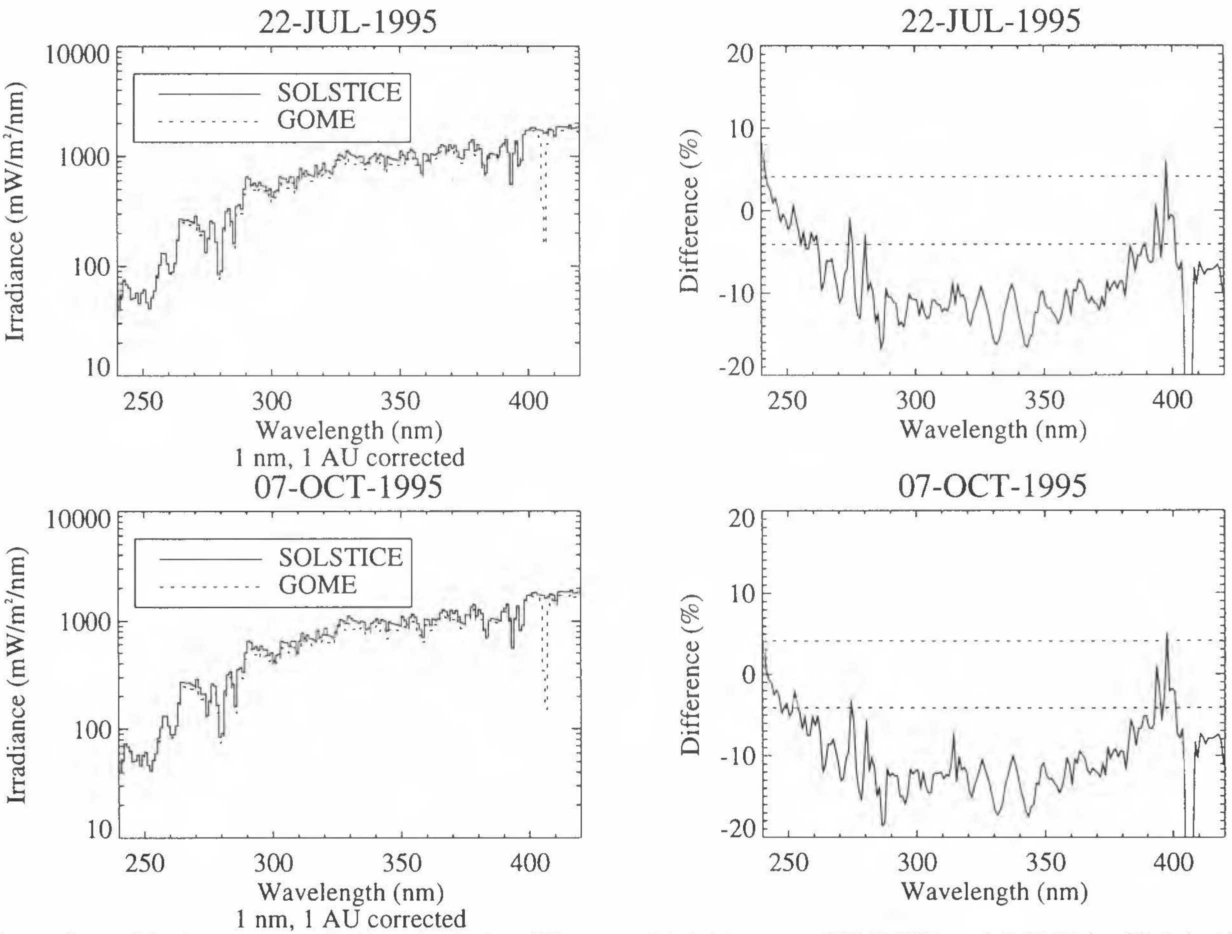

Figure 2a and b. *Raw spectra (left) and relative differences (right) between SOLSTICE and GOME for 22 July 1995 (a) and 7 October 1995 (b). Both spectra* are *reduced to 1 nm intervals and normalized to 1 AU. The dashed lines in the difference plots indicate the SOLSTICE 2-σ uncertainty (±4%) based on the recent UARS/ATLAS comparison (Woods et al., 1996).*

These wavelength dependent differences are compute for each pair of coincident SOLSTICE/GOME spectra. However, the most striking differences are identified on the first comparison and are reasonably constant in each subsequent comparison. Figure 2a and 2b display both the raw spectra and the relative difference between GOME and SOLSTICE expressed in percent for 22 July 1995 (a) and 7 October 1995 (b). SOLSTICE average ±2σ uncertainty is indicated by a pair of dashed lines on the difference plots. This uncertainty is approximated as the average over that specified wavelength range from the recent UARS/ATLAS comparison (Woods et al., 1996).

The discrepancies at the overlap region between channels 2 and 3 (around 400 nm) show up immediately. On the other hand, the matching between channel 1 and 2 (307 nm) is rather successfully controlled. The (2-3) overlap problem has been recognized from the beginning and will be addressed in the future.

The agreement between SOLSTICE and GOME is reasonably good around 250 nm and above 390 nm. However, there is a marked deviation with a characteristic parabolic shape between 300 and 370 nm that can be as high as 13%. According to TPD, the disagreement may originate from changes in the instrument response between air and vacuum operation (Zoutman et al., 1995). Studies are in progress at TPD to resolve this problem. The average deviations can be summarized in the following table:

	Average differences w.r.t. SOLSTICE (%)			
Date	240-250	250-300	300-370	370-400
22 July	1.9	-8.1	-11.8	-6.2
24 Aug	-2.0	-8.3	-12.1	-6.3
14 Sept	-0.5	-9.4	-12.5	-6.6
7 Oct	-1.7	-10.2	-12.8	-6.9

We are encouraged that the deviation has globally increased between these two different times by only 1 to 2%. We discuss this behavior in the section 3.3.

The last feature that we consider on these plots is the so-called "etalon effect". This effect is caused by constructive and destructive interferences of light that falls on the detector arrays. The light is first internally reflected in the passivating SiO_2 layer and possibly in a thin layer of ice that is formed on the cooled detector arrays. During the preflight investigations, it was found that the etalon structure shifted considerably in time due to the forming and increasing of an ice layer on the detector. It was predicted that the shift of the etalon structure in flight would be much smaller due to the almost perfect vacuum conditions in the in-flight

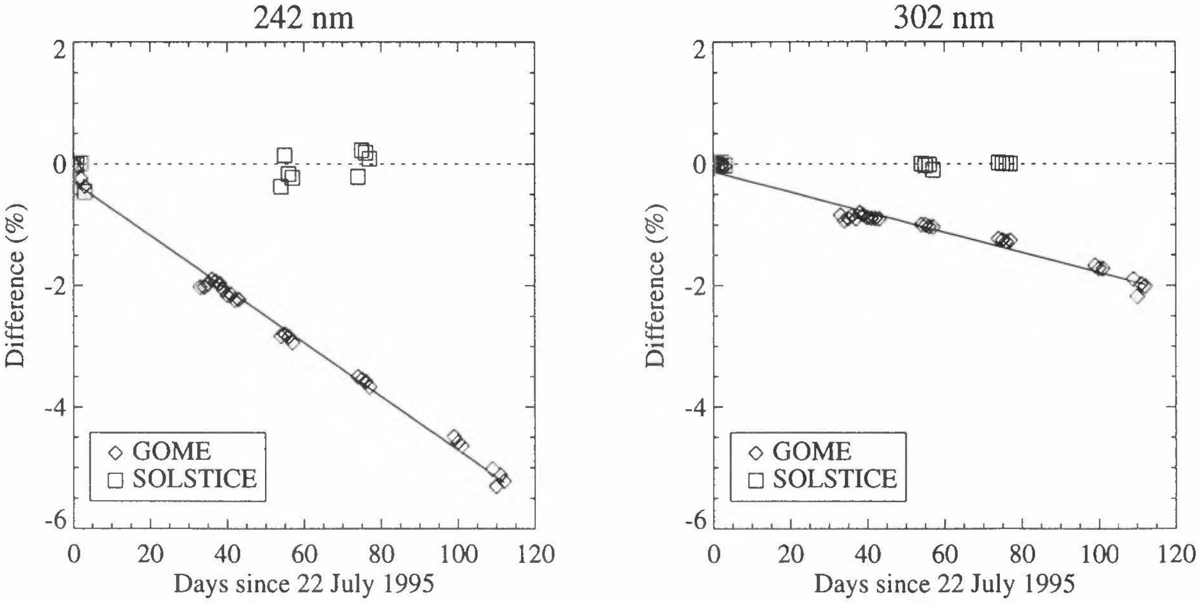

Figure 3. *Difference of the integrated irradiance within 4 nm relative to 22 July 1995 at 242 nm (left) and 302 nm (right). Both SOLSTICE (square) and GOME (diamond) are displayed as well as a linear fitting of the GOME values.*

condition. This etalon structure can be easily identified on the GOME/SOLSTICE ratio and is characterized by a long wavelength modulation beginning around 340 nm. This structure shows up also at longer wavelengths (440 and 640 nm) but is not displayed here since it is beyond the common SOLSTICE-GOME wavelength window. It is hoped that the etalon structure will reach a stable condition in order to be accurately accounted for in the radiance response function.

3.3. GOME degradation analysis

We have seen previously that the GOME/SOLSTICE ratio increases with time. We expect the GOME instrument response to slowly evolve and degrade in time, a common behavior of spaceborne instruments.

To quantify this degradation, we continually compute the ratio with respect to an average reference spectrum. We select the spectrum of 22 July 1995 as our reference spectrum and evaluate the evolution of the ratio:

$$D(\lambda,t) = \left(\frac{I_t(\lambda)}{I_{ref}(\lambda)} - 1 \right) \tag{4}$$

Each irradiance value is averaged over 4 nm band (λ±2nm) and plotted against time. The same procedure is applied to the SOLSTICE irradiance taking the spectrum for UARS day 1410 (referenced to the launch date of UARS) as reference.

The results are displayed in figure 3 for λ=242 nm and λ=302 nm. The most striking feature is the linear decrease of the GOME irradiance for the period considered. At 242 nm, the irradiance decreases at a rate equal to -0.044 %/day, and -0.016 %/day at 302 nm. Thanks to its reliable stellar calibration, SOLSTICE does not exhibit any significant drift over that period. We are reasonably confident in the fact that SOLSTICE measures the "real" solar flux. However, several SOLSTICE values have been removed from this comparison. They correspond to the days when the UARS satellite is in a configuration such that the solar arrays may significantly (about 1%) enhance straylight in the SOLSTICE spectrometer and corrupt those measurements. The SOLSTICE data processing algorithms are now being improved to remove these corrupted values.

We are particularly surprised by the very low spread of the GOME measurements, and the data fit very well the linear regression. The day-to-day measurements exhibit a very good accuracy. Removing the linear trend, the residual "noise" for 242 nm is significantly below 1% and likely a true solar variability.

To compare the GOME degradation to SOLSTICE, we have plotted in figure 4 the stellar correction coefficient of SOLSTICE from the beginning of its operation (October 3, 1991). We have overlaid the measured GOME degradation. The GOME degradation rate is surprisingly close to the stellar correction applied to SOLSTICE instrument in its early days of operation. The observed degradation rate of GOME is quite reasonable and similar in magnitude instruments as SOLSTICE's degradation rate. Note however that the time scale is defined as the real calendar day and not the total exposure time. SOLSTICE exposure time is 8 hours per day while GOME operates in solar measurement mode only for 40 seconds per day.

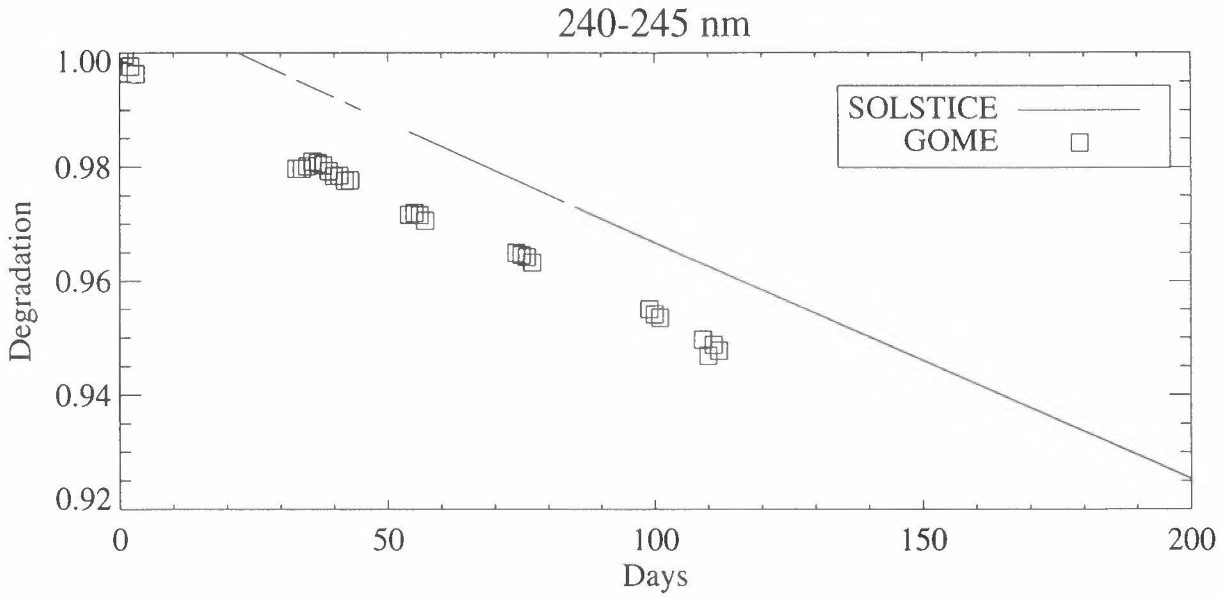

Figure 4. *Stellar degradation rate of the SOLSTICE instrument in the 240-245 nm range (solid line) during its first 200 days of measurement compared to the degradation of the GOME instrument at 242 nm.*

Not surprisingly, the highest degradation rate is found in the UV short wavelength region (≈250 nm). The higher energy of this radiation is perhaps more efficient to degrade the optical coatings or the diffuser. However, the whole wavelength range from 240 to 790 nm show degradation at different rates as depicted in figure 5a and 5b. Figure 5a displays the degradation rate for wavelength in the GOME-SOLSTICE window (240-420 nm). The maximum (in absolute value) is found at 240 nm and the degradation gets smaller for longer wavelengths. Unfortunately, the etalon effect prevents us from distinguishing between the degradation rate and the etalon modulation. Applying a rough smoothing, one can eventually identify the overall degradation rate for the whole GOME wavelength range (Fig. 5b).

4. CONCLUSIONS

So far, 30 GOME solar irradiance spectra have been received and analyzed. These include spectra from July, August, September, October and November 1995. SOLSTICE level 3BS merged spectra have been used for calibration and validation of wavelength, irradiance and instrument degradation. As far as possible, the most recent SOLSTICE calibration files have been used for the year 1995. Though possible modifications may be provided in the future, we anticipate a maximum change of 1 or 2% near 250 nm and much less for longer wavelength.

Wavelength consistency has been checked in the common GOME-SOLSTICE wavelength window of 240 to 420 nm. There are no significant discrepancies between GOME and SOLSTICE when the two data sets are intercompared at the same effective spectral resolution.

Irradiance validation shows that GOME displays a systematic offset with respect to SOLSTICE. Since we are reasonably confident in SOLSTICE uncertainty based on previous UARS/ATLAS validation, this discrepancy likely originates in the changes of pre-flight/in-fly calibration of GOME, probably due to changes in the diffuser and component optical coating characteristics. This offset needs to be further studied. The deviation shows a characteristic parabolic shape curve between 260-370 nm.

The instrument degradation is analyzed by comparing selected wavelength integrated irradiance with respect to an arbitrary reference date (22 July 1995). In the UV, the GOME instrument irradiance exhibits a marked linear decrease of the absolute irradiance. The maximum decreasing rate is found at short wavelength (240 nm) and is of -0.04%/day. The degradation decreases (less degradation) for increasing wavelength. However, the degradation analysis is perturbed by the etalon structure around 350 nm. Compared to SOLSTICE's early instrumental degradation, GOME degradation rates are of similar magnitude. These rates are reasonable for satellite-borne optical instruments subjected to highly energetic solar fluxes. Furthermore, comparing day-to-day irradiance, the GOME instrument displays a very good precision of less than 0.5%.

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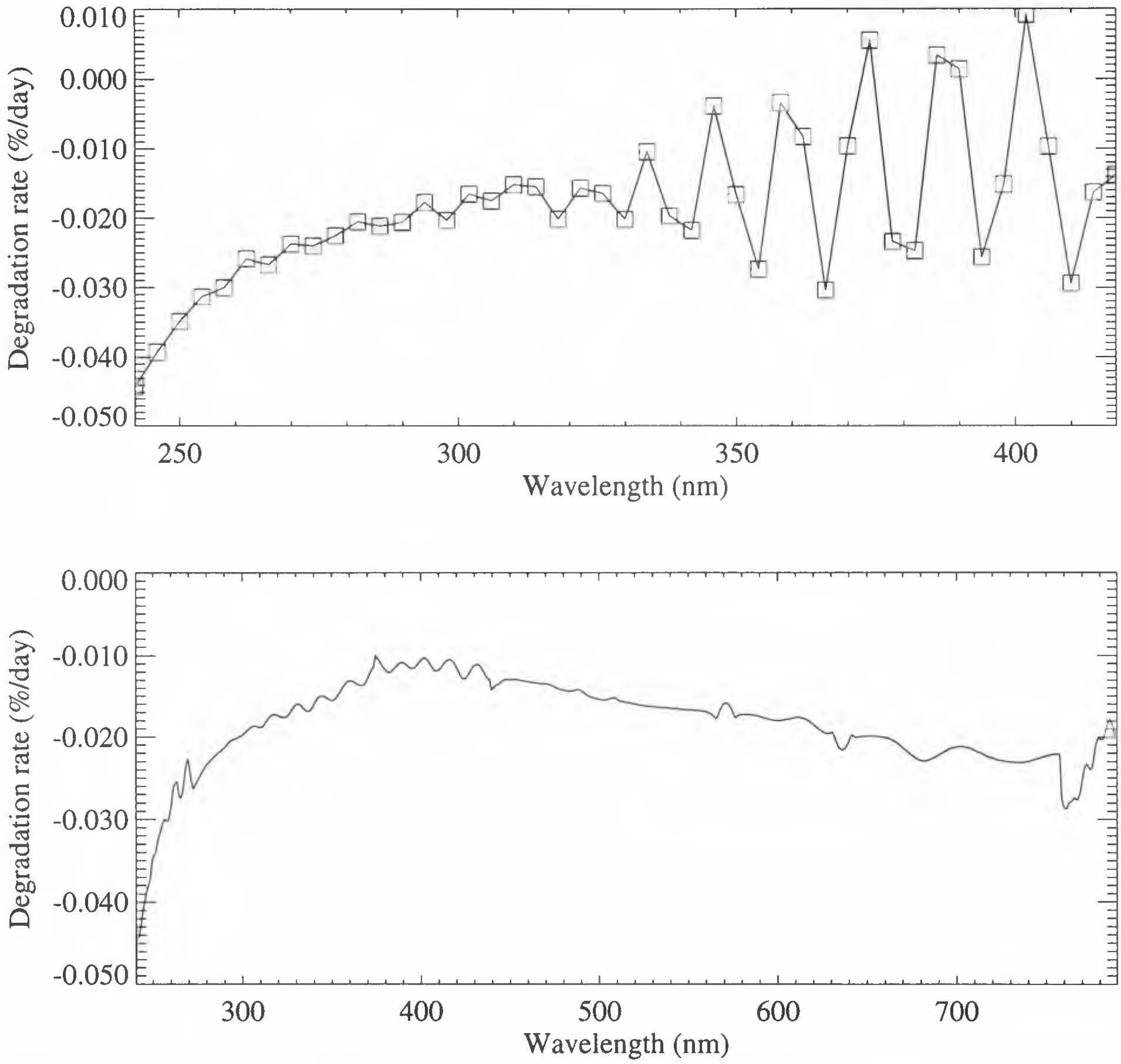

Figure 5. *(a) GOME degradation rate for the 240-420 nm range estimated from the linear regression of the integrated irradiance over 100 days of measurements. (b) Degradation rate for the whole GOME spectral range. Etalon structure and dichroic structure have been smoothed out.*

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