GOME SOLAR IRRADIANCE VALIDATION USING UARS SOLSTICE DATA

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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 paper we concentrate on a validation 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%. 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 on board 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 reader is referred to ESA reports [2, 3] for details about the GOME instruments.

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.

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In the work 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 two to four 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 and characteristics are described below in Section 2. Section 3 defines the data sets used in this study and section 4 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 instruments resolutions, the irradiance validation (differences in absolute calibration) and trends that can be established in the GOME instrument response. In section 7, we present an attempt to evaluate GOME precision with respect to SOLSTICE. Finally, in Section 8 we give our conclusions.

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.

The reader is referred to papers by Rottman *et al.* (1993) [6], Woods *et al.* (1993) [7], and Woods *et al.* (1996) [8] 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.

The validation of the SOLSTICE solar irradiances was a joint effort of four solar UV irradiance programs [8]. To summarize, measurements from the four instruments agree to better than the 2σ 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.

3. DATA SETS

Up to now, the GOME level 1 data set used in this work is restricted to the available GDP V1.0 from July 1996 to December 1996. We have restricted our analysis to this time period because, during this interval, the GOME instrument has performed without any cooler switch off. Hence, the solar measurements are not perturbed by induced temperature variation. While limiting the available time period, this provides an homogeneous data sets.

As far as possible, time coincident SOLSTICE irradiance spectra are retrieved from the LASP database, and we have used the "level 3BS merged" high resolution products. This product is the SOLSTICE solar measurements at instrumental resolution corrected for scattered light, detector linearity, detector dark counts, detector gain changes, instrument sensitivity and degradation. It is also normalized to one astronomical unit.

SOLSTICE data used in this work are the most recent version 9 data. More specifically, new calibration parameters taking into account revised stellar pointing information have been applied to the full SOLSTICE data. One have to be particularly careful when comparing GOME and SOLSTICE time series not to confuse instrumental changes with real solar variability. Newly corrected SOLSTICE V9 data are now better corrected for instrumental artifacts and have been exclusively used.

4. RESOLUTION COMPARISON

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 ($\Delta\lambda \approx 0.25$ nm) and 1.8 for the N channel ($\Delta\lambda \approx 0.35$ nm). The differences between SOLSTICE and GOME resolution can be seen in Figure 1 where both irradiances are plotted at instrumental resolution for the same day. One can clearly identify in the GOME spectrum features missing in the SOLSTICE spectrum. Figure 1 also include a high resolution ground based spectra (Ref. [5]) convolved with the SOLSTICE effective bandpass. The different features and structures match very well between the two spectra and there is no significant discrepancies between GOME and SOLSTICE with respect to the wavelength calibration.

5. IRRADIANCE VALIDATION

Both SOLSTICE and GOME irradiances are normalized to 1 astronomical unit (AU). Each spectra is interpolated to a common wavelength scale of 0.025 nm grid (Woods *et al.* [8]) and then convolved to a 1 nm grid, centered at half nm from 240 to 400 nm.

The relative irradiance differences between GOME and SOLSTICE is defined as

$$\Delta(\lambda) = \left(\frac{I_{GOME}}{I_{SOL}} - 1\right) \quad (1)$$

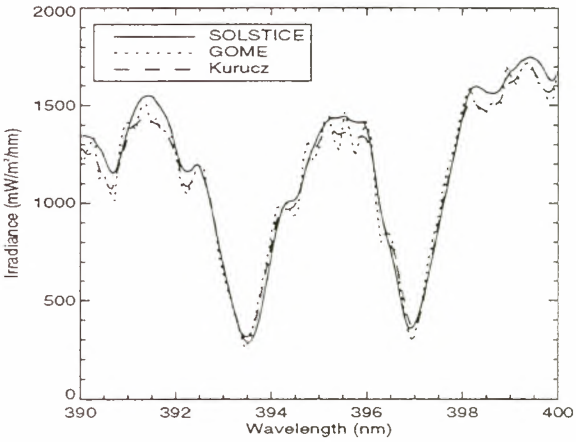

Figure 1: One wavelength regions from SOLSTICE and GOME irradiance at instrumental resolution showing the differences in resolution. Also show is a very high resolution, ground-based, solar spectrum convolved to SOLSTICE effective bandpass.

The differences are displayed for three particular days in figure 2. The first curve of 3 July 1995 while not within our initial prescribed time period, is still a version 1.0 level 1 GOME data. The agreement between SOLSTICE and GOME is reasonably good above 300 nm. However there is marked deviation for shorter wavelength. This deviation increases from ~ 4% below 300 nm in July 1995 to ~ 10% in July 1996 and down to ~ 16% in December 1996 and is wavelength dependent. The deviation above 300 nm does not show such a marked increase and is ±5% with large wavelength dependencies due to the etalon effect.

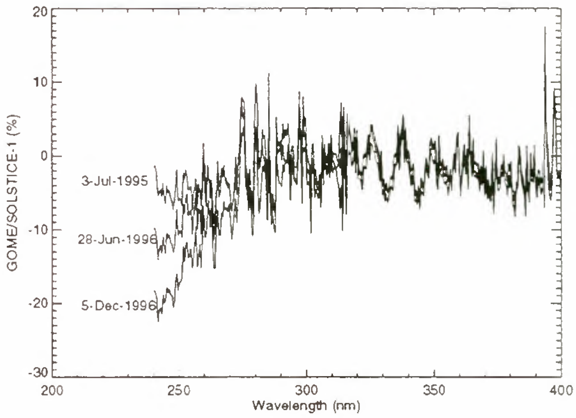

Figure 2: The relative difference of GOME with respect to SOLSTICE for 3 particular days expressed in %.

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. 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. These etalon structures are highly sensitive to temperature variation of the instrument and perturb considerably the cross-validation of the instrument. This problem is known from the beginning and is still investigated. It is hoped that the etalon structure will reach a stable condition in order to be accurately accounted for in the radiance response function.

6. GOME DEGRADATION ANALYSIS

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

For this analysis, it is important to minimize as much as possible the possible SOLSTICE instrumental changes. In the time series we have made use of the much improved (but still preliminary) version 9 SOLSTICE data. While SOLSTICE version 9 data are now available for the entire UARS mission, we have only considered the consistent GOME version 1.0 time series for the year 1996, i.e. from June 28, 1996 to November 8, 1996. To quantify this degradation, we continually compute the ratio with respect to an average reference spectrum. For this analysis, We select the spectrum of 28 June 1996 as our reference spectrum and evaluate the evolution of the ratio:

$$D(\lambda, t) = \left(\frac{I_\lambda(t)}{I_\lambda(t_0)} - 1 \right) \qquad (2)$$

Each irradiance value is averaged over 5 nm band ($\lambda \pm 2.5$nm) and plotted against time. The same procedure is applied to the SOLSTICE irradiance taking the spectrum for UARS day 1752 (referenced to the launch date of UARS) as reference. While somewhat short, the available V1.0 GOME time series is sufficient to extract the most prominent features.

The results are displayed in figure 3 for $\lambda = 242$ nm and $\lambda = 302$ nm. The most striking feature is the exponential decay of the GOME irradiance for the period considered. An exponential decay function is fitted onto the GOME data according to

$$A_0 \left(e^{-t/A_1} - 1 \right) \qquad (3)$$

At 242 nm, some large deviations in the SOLSTICE measurements show up in August 1996. This instrumental problem is known and will be corrected. At 242 nm, the decay rate is 128 days (A_1) with an amplitude A_0 equal to 10.5%. Both the rate and the amplitude decrease for longer wavelengths reaching values close to zero above 350 nm. These results are summarized in Figures 4 which display the values of the fitted coefficients A_0 and A_1 from 240 to 400 nm. Note also that the 27 days solar modulation is noticeable on both SOLSTICE and GOME time series.

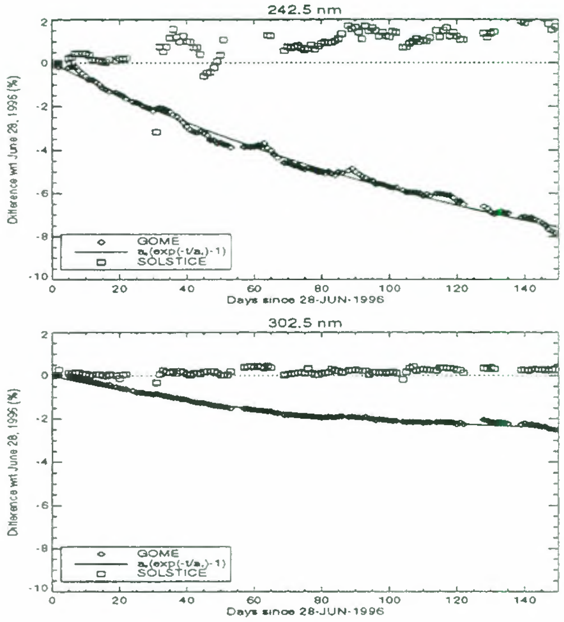

Figure 3: Difference of the integrated irradiance within 5nm relative to 8 June 1996 at 242 nm (above) and 302 nm (below). Both SOLSTICE (V9) (square) and GOME (V1.0) (diamond) are displayed as well as a exponential decay fitting of the GOME values.

7. GOME DAY-TO-DAY PRECISION

Figures 3 already give us some insight of the very good day-to-day precision of the GOME measurements. The instrumental noise level is very low and the 27 days solar rotational modulation shows up nicely at 242 nm. In the sequel, we make an attempt to characterize quantitatively the day-to-day precision of GOME measurements.

Several sources of errors perturb the data set we are analyzing. They include the instrument degradation in the UV and the etalon variation with time. We also need an independent external source for the real solar variability. In this analysis, we choose SOLSTICE measurement as external source.

The first step is to extract from the GOME data the wavelength dependent degradation rate as well as any possible slow etalon change using a non linear least square fit of the form

$$A_0 + A_1 e^{-(t-t_0)/\tau}$$

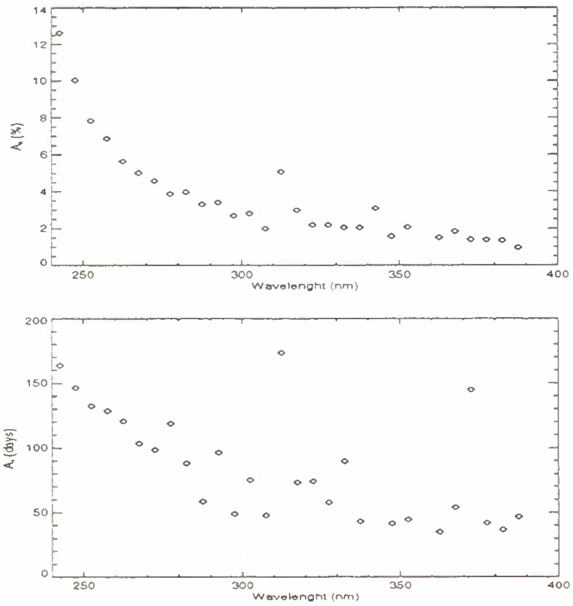

Figure 4: Fitted coefficient A_0 (above) from 240 to 400 nm giving the amplitude of the fitted exponential decay and A_1 (below) giving the decay rate of the fitted exponential.

where t_0 is a reference day, July 3, 1996. Let $G(\lambda, t)$ and $S(\lambda, t)$ be GOME and SOLSTICE measured irradiance respectively, both convolved to the same wavelength grid of 1 nm. The function 4 is fitted on the absolute difference $G(\lambda, t) - G(\lambda, t_0)$. The coefficient $A_0(\lambda)$, $A_1(\lambda)$ and $\tau(\lambda)$ include the above instrument degradation as well as the possible slow etalon variation but not the short time scale solar variability. The new corrected GOME data sets defined by

$$G_1(\lambda, t) = G(\lambda, t) - A_0 - A_1 e^{-(t-t_0)/\tau} \quad (5)$$

still display a constant residual offset with respect to SOLSTICE. This residual includes the GOME degradation and etalon state as well as any unknown systematic offset at the initial time t_0. We remove the residual from G_1 and rescale GOME to SOLSTICE by defining a new "corrected" GOME irradiance G_2 and computing the relative difference w.r.t. SOLSTICE, R:

$$\begin{aligned} G_2(\lambda, t) &= G_1(\lambda, t) - [G(\lambda, t_0) - S(\lambda, t_0)] \quad (6) \\ R &= \left(\frac{G_2}{S} - 1\right) \quad (7) \end{aligned}$$

The statistical properties of R give us an idea of GOME day-to-day precision w.r.t. SOLSTICE or at least an upper limit estimate since, in this process, we are adding SOLSTICE intrinsic instrumental noise to G_2. Figures 5 display for two wavelengths the initial time series, the corrected time series and the ratio R. This give us an idea of the kind of measurements can be expected from GOME if the degradation and etalon was characterized. Figure 6 shows the mean and 2σ values from 240 to 400 nm (channel 1 and 2). There is still a small offset in channel 1 ($\lambda < 300$ nm) and the standard deviation is around 1%. This residual offset originates from the SOLSTICE F channel. A small linear trend is still visible in this channel which manifests itself by an offset of the average irradiance ratio and larger than expected standard deviation. There is no residual offset left in channel 2 (and no trend in SOLSTICE N channel) and the standard deviation is less than 0.5%. This gives us a first estimate of the very good day-to-day precision of GOME.

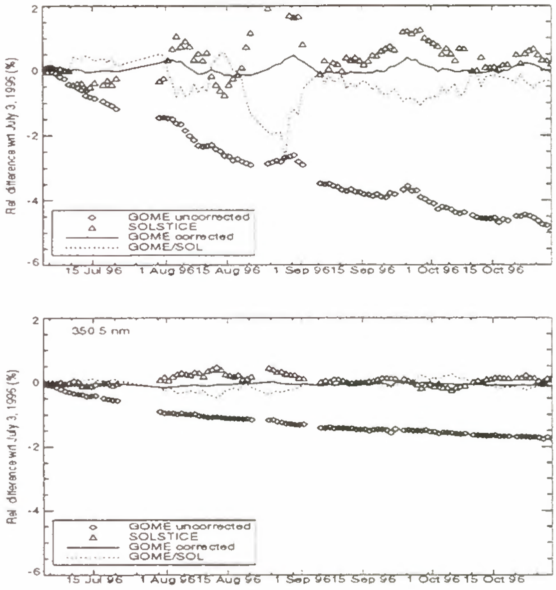

Figure 5: Original and corrected GOME time series at 250 nm (above) and 350 nm (below). The SOLSTICE time series is also shown as well as the relative difference R.

However, we should stressed that this procedure is only valid as long as the etalon feature is stable. Any cooler switch off induces significant jump in the etalon behavior and the fitting process fails. In this case, a piecewise fitting process between every etalon jumps should be applied.

8. CONCLUSIONS

6 months of GDP V1.0 GOME solar irradiance spectra have been analyzed. These include spectra from June to December 1996. SOLSTICE level 3BS merged spectra V9.0 have been used for calibration and validation of wavelength, irradiance and instrument degradation. The most recent SOLSTICE calibration files have been used for the year 1996. The

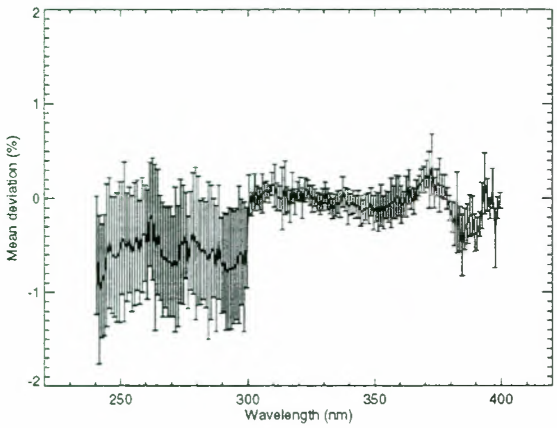

Figure 6: Mean value and 2σ of the relative difference R from 240 to 400 nm averaged over 6 months data set.

SOLSTICE V9.0 data will be made publicly available as part of the SOLSTICE database at the Goddard DAAC in the near future (http://daac.gsfc.nasa.gov).

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 for this time period 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. While the radiometric response has been already corrected for some air-to-vacuum effect with respect to pre-version 1.0 level 1 data (Ref. [4]), there is still a significant offset in the UV ($\approx$ 250 nm).

The instrument degradation is analyzed by comparing selected wavelength integrated irradiance with respect to an arbitrary reference date. In the UV, the GOME instrument irradiance exhibits a marked exponential decay of the relative irradiance response. The maximum decreasing rate of 10% for 6 months is found at short wavelength (240 nm). The degradation decreases (less degradation) for increasing wavelength and is less than 2% for 6 months of measurements. 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. Note however that recent investigations at ESA/ESTEC and ESA/ESRIN show that the diffuser does not exhibit any marked degradation that could explain the observed changes in the instrument response. Further investigations are in progress to monitor any possible changes in optical coating characteristics.

GOME day-to-day precision is estimate by removing of the exponential decay as well as any long time scale etalon variation. The "corrected" GOME spectrum is rescaled to a reference SOLSTICE spectrum. The averaged relative difference between GOME and SOLSTICE solar measurement gives a rough estimate of GOME day-to-day precision. The 2σ deviation is around 1.5% in channel 1 but is mainly due to a small residual linear trend in SOLSTICE measurements. However, standard deviation is less than 0.5% in channel 2. This preliminary estimate shows the very good precision and the low noise level that can be obtained with the GOME instrument.

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