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Ground-based determination of the spectral ultraviolet extraterrestrial solar irradiance: Providing a link between space-based and ground-based solar UV measurements

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Abstract. The extraterrestrial solar spectrum between 295 and 355 nm has been determined from direct irradiance measurements made with a Brewer double spectrophotometer, using the Langley method. The measurements in this study consist of 449 half days of data collected during 1998 at Mauna Loa Observatory, Hawaii. The ±2.3% accuracy of this extraterrestrial solar spectrum is obtained by a careful investigation of the instrument calibration and the systematic errors that can arise because of atmospheric and instrument instabilities as well as finite slit width effects and is limited by the uncertainty of the absolute irradiance scale transfer between the standard laboratory and the instrument. A comparison between this extraterrestrial solar spectrum measured from the ground with the mean UARS and ATLAS-1 spectrum show an agreement better than 3%. The mean ratios are 1.002 for the mean UARS spectrum, 1.003 for the mean ATLAS-1 spectrum, 1.013 for the SOLSPEC spectrum, and 1.017 for the ATLAS-3 spectrum.

1. Introduction

The solar irradiance, especially below 350 nm, is important for the study of the photochemical reactions occurring in the atmosphere. Furthermore, ground-based measurements of absolute solar irradiance are used in conjunction with radiative transfer models to improve our understanding of the processes affecting the radiation transfer through the atmosphere. One important input parameter into these calculations is the extraterrestrial solar irradiance. Traditionally, it has been obtained either from ground-based measurements or from measurements onboard rockets or aircrafts [*Arvesen et al*., 1969; *Broadfoot*, 1972; *Neckel and Labs*, 1984]. However, in recent years, extraterrestrial solar spectra have been obtained by instruments located outside the terrestrial atmosphere to avoid atmospheric absorption and scattering effects and allow measurements at wavelengths shorter than 290 nm where ozone and oxygen absorb all incident radiation. For a discussion on the measurement history of the solar irradiance, see, for example, *DeLand and Cebula* [1998].

In this study we will use the mean solar spectrum obtained on March 29, 1992, by the UARS SUSIM and SOLSTICE spectrometers located on the Upper Atmosphere Research Satellite (UARS) and presented by *Woods et al*. [1996]. This solar spectrum is available at the wavelength range 119.5–410.5 nm at 0.1 nm intervals with a resolution of 1.1 nm. The ATLAS (Atmospheric and Terrestrial Laboratory for Application and Science) missions onboard the space shuttle in March 1992 (ATLAS 1), April 1993 (ATLAS 2), and November 1994 (ATLAS 3) also measured absolute solar irradiances with three spectrometers (SOLSPEC, SUSIM, and SSBUV) [*Cebula et al*., 1996; *Thuiller et al*., 1997]. The mean ATLAS-1 spectrum based on data from the three spectrometers obtained on March 29, 1992, was compared to the mean UARS spectrum and agreed to within 3% [*Cebula et al*., 1996]. In recent years a high-resolution solar spectrum obtained during the ATLAS-3 mission on November 13, 1994, has been increasingly used for radiative transfer calculations requiring a high-resolution spectrum [*Bais*, 1997; *Mayer and Seckmeyer*, 1997; *Kylling et al*., 1998; *Lenoble*, 1998; *Pachart et al*., 1999]. However, since this spectrum has not been validated so far, this introduces uncertainties in the results of radiative transfer calculations which need to be resolved and which will be addressed in this study.

In this study we present a 10 month record of ground-based measurements of the extraterrestrial solar spectrum obtained from Langley analysis of direct irradiance measurements in the range 295–355 nm. The methodology has been used previously, but no account has been made of several systematic effects that need to be taken into account when comparing the extraterrestrial spectrum from spaceborne and ground-based instruments. In particular the strong absorption by ozone below 310 nm requires a careful study of the effects of the slit function of the instrument on the retrieved extraterrestrial spectrum. Furthermore, a long time series of measurements is required from which a representative average extraterrestrial spectrum can be constructed and variability due to atmospheric effects can be determined.

2. Instrumentation and Methodology

In November 1997 a double monochromator Brewer spectrophotometer (Brewer 119) was installed at Mauna Loa Observatory, Hawaii (3397 m above sea level (asl), longitude 155.578°, latitude 19.539°) to monitor solar UV irradiance and total column ozone. The double Brewer spectrophotometer is constructed with two Ebert-Fastie-type monochromators used in a recombining mode [*Kerr et al*., 1984; *Bais et al*., 1996]. A horizontal piece of Teflon is used as a transmitting diffuser for measuring global UV irradiances. For absolute direct irradi-

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ance measurements, a rotating prism reflects incoming radiation into the optical path of the instrument and adjusts to the zenith angle of observation, while the azimuth setting is determined by the rotation of the whole instrument about its vertical axis. An iris diaphragm controls the field of view of the direct irradiance port and can be set to between 1.5° and 10°. A thin quartz diffuser is placed behind the iris to make the instrument insensitive to slight optical misalignments. Up to five different "near-neutral" density filters with an increasing attenuation of $\sim 10^{0.5}$ can be placed into the beam path to reduce the light intensity. The transmission of these neutral density filters is known to better than ±0.5% over the wavelength range 285–355 nm. So far, no change in filter transmission with time has been detected. The instrument has a novel grating drive mechanism that is accurate to better than ±0.005 nm over the range of the instrument (280–355 nm) [*Gröbner et al.*, 1998]. Its wavelength scale is based on scanning a set of emission lines from spectral discharge lamps. The resolution of the instrument is slightly dependent on wavelength, decreasing from a band pass measured as the full width at half maximum (FWHM) of 0.59 nm at 290 nm to 0.51 nm at 350 nm. The radiometric calibration is based on 1000 W DXW tungsten-halogen lamps traceable to the National Institute of Standards and Technology (NIST). The lamps used in this study were specially calibrated by NIST in their horizontal position as used by the Brewer spectrophotometer with an uncertainty estimated to be not larger than ±2% over the wavelength range 285–355 nm [*Early et al.*, 1998].

2.1. Direct Irradiance Calibration

The radiometric laboratory calibration which is normally applied to the global irradiance port (diffuser) must be transferred to the direct irradiance port. This transfer is obtained by alternating measurements of direct solar irradiance through the two ports. The diffuse (scattered) radiation is blocked on the global irradiance port by using a shading tube placed above the diffuser. For this comparison, the field of view of the direct irradiance port is matched to the 10° field of view of the shading tube by opening the iris to 10°. The amount of forward scattered radiation falling in the 10° field of view of the direct irradiance port was measured by alternate measurements with the iris closed (~1.5°) and open (~10°) and was measured to be less than 2% of the direct irradiance. Therefore a possible systematic error due to any mismatch between the field of view of the open iris and of the shading tube is negligible.

Measurements at several wavelengths are alternated 5 times between the global and the direct irradiance port. Each set of measurements is interpolated to a common air mass and corrected for the cosine error of the diffuser at this particular solar zenith angle. The total calibration transfer takes about 20 min at the wavelengths 295, 300, 305, 310, 315, 325, 335, 345, and 355 nm and was performed at solar zenith angles between 11° and 77°.

The final direct to global calibration transfer function is averaged over measurements obtained during four different days at Mauna Loa where observing conditions are generally stable. The calibration transfer uncertainty based on the individual scatter of these measurements is estimated at ±0.5%.

2.2. Measurement Procedure

A direct irradiance measurement consists of a wavelength scan over the range 285–355 nm every 0.5 nm and requires ~6 min. In total, between 25 and 35 direct irradiance measurements are obtained each day. Before each measurement the wavelength scale is referenced to the 297 nm emission line from the internal mercury lamp thereby minimizing any remaining temperature effect of the grating drive. The spectral stretching due to temperature has been measured at 1.2×10^{-5} K^{-1} (i.e., a wavelength change of +0.0004 nm K^{-1} at 355 nm). The temperature dependence of the sensitivity is less than ±0.1% K^{-1} over the wavelength range as estimated from comparisons with 20 other spectrometers during the international SUSPEN campaign in 1997 in Nea Michaenonia, Greece [*Gardiner and Kirsch*, 1997].

2.3. Langley Extrapolation

An extraterrestrial spectrum is obtained from a Langley analysis of one-half day of measurements and consists of about eight direct irradiance scans in the air mass range 1.2–3, the air mass being defined as the path length through the atmosphere between the instrument and the Sun relative to the vertical path length. A description of the method and a discussion of potential errors can be found in the works of *Dutton et al.* [1994] and *Harrison and Michalsky* [1994]. For measurements at 300 nm the maximum air mass is limited to 2.2 since the detected signal becomes small. Each wavelength is regressed separately against air mass by the following equation, which is derived from the Bouguer-Lambert law:

$$\log I^{\lambda} + \tau_{\mathrm{air}}^{\lambda} m_{5\,\mathrm{km}} = \log I_0^{\lambda} - \tau^{\lambda} m_{22\,\mathrm{km}}, \qquad (1)$$

where $\tau_{\mathrm{air}}^{\lambda}$ is the optical depth due to the scattering by air molecules calculated using the formula by *Nicolet* [1984], $m_{5\,\mathrm{km}}$ and $m_{22\,\mathrm{km}}$ are the air masses for a layer at 5 km and 22 km, respectively, above the measuring station. Background aerosols are treated as occurring in the layer at 22 km. Results from regressing the measurements in (1) are the extraterrestrial irradiance I_0^{λ} and the optical depth τ^{λ} at each wavelength λ. The optical depth τ represents the remaining absorption of the incident solar beam, essentially by ozone at short wavelengths and by aerosols.

The results from such an analysis are shown in Figure 1 for measurements obtained during the morning of April 5, 1998. Panel a shows the optical depth τ with the characteristic absorption features of ozone in the Huggins band which are shown enlarged in panel b. The residual optical depth of 0.05 at 355 nm is due to aerosols in the atmosphere and is in good quantitative agreement with measurements obtained at this site and equivalent sites [*Dutton et al.*, 1994]. Panel c displays the correlation at each wavelength between the measurement data and (1). Because of the strong absorption of ozone at short wavelengths and its stability during the day, most of the variability observed during the Langley regression stems from the variability of aerosols. Since at short wavelengths the absorption of aerosols is negligible compared to the absorption by ozone, there is no discernable deviation from the Bouguer-Lambert law and the correlation is 1. Panel d, Figure 1, shows the extrapolated irradiance values to zero air mass normalized to the standard Sun-Earth distance (1 astronomical unit (AU)). If air masses below 1.2 are included in the analysis, the correlation coefficient is slightly decreased without changing significantly the extrapolated extraterrestrial spectrum I_0 or the optical depth τ. Similarly, increasing the air mass range to 4 or 4.5 also has no noticeable effect on the retrieved parameters. Finally, results from an air-mass-weighted regression also agreed very well.

The measurements span the period January 1 to October 2, 1998, with a total of 449 half days of data. The instrument was recalibrated between March 23 and April 10, 1998. Some days are missing due to occasional instrument malfunctioning which ultimately led to the temporary end of routine observations at the beginning of October 1998. Measurements have since resumed after the instrument was repaired and recalibrated in March 1999.

3. Discussion

3.1. Average Extraterrestrial Spectrum

The average extraterrestrial spectrum for the whole measurement period is obtained by screening the data based on the average correlation coefficient (CC) of all wavelengths for each half day. The screen criterion was chosen to remove obvious outliers on the one hand and to use as many measurements as possible on the other hand. The average extraterrestrial spectra obtained with different cutoff criteria (i.e., from CC above 0.97 to above 0.995) were very similar (differences below ±0.5%), thus showing the robustness of the method. Finally, a criterion of CC ≥ 0.985 was chosen which left 181 half days in the analysis well distributed over the measurement period (for comparison, using CC ≥ 0.995 left 75 half days in the analysis). From now on we will only refer to the measurement set selected by applying the criterion CC ≥ 0.985.

Figure 2 shows the time evolution of extraterrestrial irradiance values at three wavelengths averaged over ±3 nm. The measurements are plotted relative to the mean values for the measurement series. The standard deviation (root-mean-square) of the measurements are ±4.9% at 300 nm, ±2.7% at 315 nm, and ±2.4% at 340 nm. The slight increase of scatter with decreasing wavelength is due to ozone variations, as is suggested by the correlation seen with simultaneously measured total ozone values (not shown).

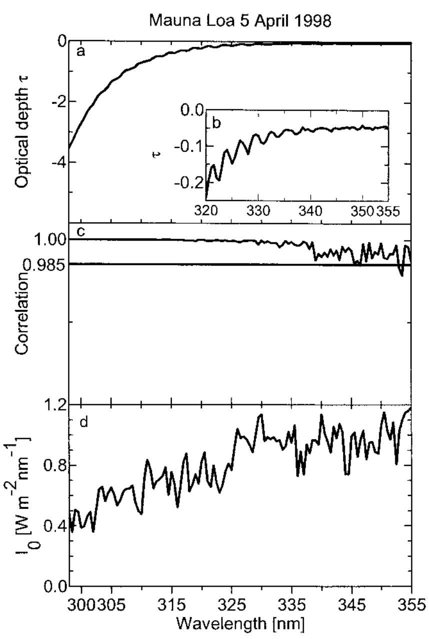

Figure 1. Results from the Langley regression for direct irradiance measurements obtained on April, 5, 1998. Panel a shows the slope of the linear Langley regression which essentially represents absorption of ozone and aerosols. The well-known ozone features around 310 nm are shown enlarged in panel b. The residual optical depth of 0.05 nm at 355 nm is probably due to stratospheric aerosols. Panel c displays the correlation coefficient (CC) between the measurements and the linear regression line. Panel d shows the extrapolated extraterrestrial solar spectrum normalized to 1 AU.

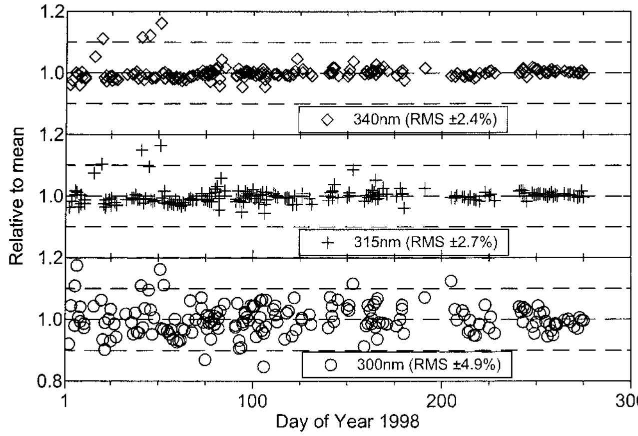

Figure 2. Time evolution of 181 extraterrestrial solar spectra obtained with the criterion CC ≥ 0.985 at three wavelength bands (center wavelength ±3 nm). The standard deviations at 300, 330, and 340 nm are 4.9, 2.7, and 2.4%, respectively. This increase in scatter with decreasing wavelength is correlated to daily total ozone variations during these measurements.

3.2. Systematic Effects

Changing atmospheric conditions or instrument instabilities introduce systematic errors in the derived extraterrestrial spectrum. By using a large set of measurements the random scatter due to changing atmospheric conditions will be described here by the standard error of the mean. Thus we assume that on average the atmospheric conditions are constant; that is, there are no systematic diurnal atmospheric variations. The following systematic effects and their influence on the extrapolated extraterrestrial spectrum were investigated and will be described in the following sections: instrument temperature, absolute irradiance calibration, spectral resolution of the spectrophotometer, air mass calculation, and systematic ozone variations.

3.2.1. Instrument temperature. Since the instrument is not temperature stabilized, there can be possible sensitivity changes due to temperature. This could introduce a systematic bias in the Langley extrapolation because the temperature consistently increases by up to 20 K during the morning. This effect was investigated by comparing half days with small and large temperature variations (for example, the temperature of the instrument was constant during most afternoons) and insignificant systematic differences were seen. Also, increasing the air mass range used for the Langley-regression analysis increases the temperature range, and this also showed an insignificant systematic effect in the retrieved extraterrestrial spectrum.

3.2.2. Calibration. The error due to the absolute irradiance calibration is mainly due to the uncertainty associated with the calibration transfer from the primary standard to the 1000 W lamps. This uncertainty is of the order of ±2%. An additional uncertainty introduced by the calibration setup is estimated to be below ±1%, which is a combination of errors in the distance of the lamp to the diffusing surface, current

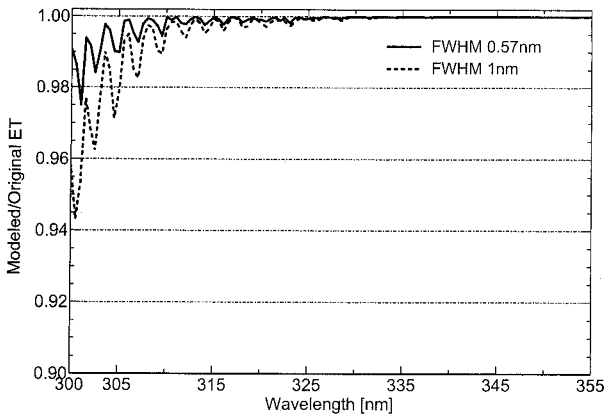

Figure 3. Ratio between an extraterrestrial spectrum convolved with the slit function of Brewer 119 and the extrapolated extraterrestrial spectrum obtained from spectra attenuated by a model atmosphere representative for conditions at Mauna Loa, Hawaii. The calculations are based on a high-resolution extraterrestrial spectrum (ATLAS 3) which was attenuated by a model atmosphere containing ozone (275 Dobson units (DU)) and at a pressure of 650 mbar. Eight spectra were calculated for air masses between 1.1 and 3, then attenuated and convolved with the slit function of the instrument (FWHM 0.57 nm). Finally, the resulting eight spectra were used to retrieve the original extraterrestrial spectrum.

control accuracy, lamp environment temperature, and stray light. The calibration transfer uncertainty from the global to the direct irradiance port, as discussed previously, is less than ±0.5%.

3.2.3. Resolution. The resolution (slit function) of Brewer 119 has an important effect on the Langley extrapolation if there is a large gradient of the measured intensity with wavelength. This is the case below 310 nm where the gradient in ozone absorption is large. The effect was quantified by modeling the measurement and Langley regression process for conditions representative for our measurements. A high-resolution extraterrestrial spectrum (ATLAS 3) was first attenuated by a model atmosphere described by Rayleigh scattering and ozone absorption representative for Mauna Loa. Several air masses in the range 1.2–3 were used. The attenuated spectra were then convolved with the slit function of the instrument and Langley-extrapolated to retrieve the extraterrestrial spectrum. The ratio of the resulting extraterrestrial spectrum to the original high-resolution extraterrestrial convolved with the slit function is shown in Figure 3 and represents a correction function that needs to be applied to the Langley extrapolated extraterrestrial spectrum. This correction function is modulated by the characteristic ozone absorption and becomes negligible above 305 nm. Between 305 and 300 nm the correction function fluctuates between 0.3% at 303.5 nm and 2.5% at 301 nm.

3.2.4. Air mass calculation. The calculation of the air masses $m_{5\,\mathrm{km}}$ and $m_{22\,\mathrm{km}}$ defined in (1) assumes that all relevant particles are located in a single layer in the atmosphere. Thus the particles responsible for Rayleigh scattering are grouped in a layer at 5 km and those for ozone absorption at 22 km above the measuring station. Since these are only approximations it is essential to estimate the uncertainty in the extrapolated extraterrestrial spectrum that arises from these assumptions.

Changes in the Rayleigh-scattering height are found to be negligible, introducing an uncertainty in the extrapolated extraterrestrial spectrum of only ±0.1% km^{-1}, whereas a height change in the ozone layer introduces a substantial uncertainty below 305 nm. The uncertainty is +0.25% km^{-1} at 305 nm and +0.55% km^{-1} at 300 nm.

3.2.5. Systematic ozone variability. Systematic ozone changes can occur through photodissociation of ozone at low air masses or through changes in the absorption of ozone due to different stratospheric temperatures. Also, geographically distinct air masses are sampled during the course of one measurement day. These effects introduce an error that was estimated to be equal or less than ±1% of total ozone. When this ozone variability is distributed over the air mass range 1.2–3, it introduces an uncertainty in the extrapolated extraterrestrial spectrum of ±3% at 300 nm and ±1% at 305 nm. Above 305 nm this effect is negligible.

3.3. Error Budget

The error budget associated with the average extraterrestrial solar spectrum is shown in Table 1. Because of the large number of measurements, 181, the standard error of the average extraterrestrial spectrum is only ±0.23% and is negligible compared to the uncertainty arising from the absolute calibration. Above 305 nm, the total uncertainty is ±2.3% by assuming all errors to be uncorrelated (root-mean-square summing). Below 300 nm the uncertainties associated with ozone variability tend to increase sharply; thus the overall uncertainty at 300 nm is 4.1% and ±6% at 298 nm. It follows from the above that the accuracy of the average extraterrestrial solar spectrum obtained from this Langley analysis is dominated by uncertainties arising from the transfer of the absolute irradiance scale from the standard laboratory to the instrument.

3.4. Comparison to the Mean ATLAS 1 and UARS Spectra

To assess the accuracy of the derived ground-based extraterrestrial solar spectrum (BREWER), we will compare it to the mean UARS solar spectrum [*Woods et al.*, 1996], the mean ATLAS-1 spectrum [*Cebula et al.*, 1996], and the mean SOLSPEC spectrum obtained during the ATLAS-1 mission [*Thuiller et al.*, 1997]. Figure 4 shows the spectral solar irradiances in the wavelength range 295–355 nm. The larger features in the BREWER spectrum are due to the higher resolution of 0.55 nm compared to the resolution of about 1 nm from the other solar spectra. To obtain a more precise comparison, we computed the ratios between the UARS, ATLAS 1, and

Table 1. Uncertainty Estimate of the Extraterrestrial Solar Spectrum Obtained From Ground-based Measurements

	Uncertainty	
Description	300 nm	>305 nm
Radiometric calibration[a]	±2.3%	±2.3%
Ozone layer height, ±3 km	±1.6%	0%
Ozone variability	±3%	0%
Standard error	±0.36%	±0.23%
Total uncertainty	±4.1%	±2.3%

[a]The radiometric calibration uncertainty consists of the root-mean-square uncertainties of the reference 1000 W lamps, ±2%, the calibration setup, ±1%, and the global to direct calibration transfer, ±0.5%.

SOLSPEC solar spectra and the BREWER spectrum shown in Figure 5. Because of differences in resolution of the various instruments, a 5 nm running mean was used to suppress some of the noise induced by the solar Fraunhofer lines. Between 300 and 340 nm the mean ratios between the SOLSPEC, ATLAS 1, and UARS spectra with the BREWER spectrum are 1.013 ± 0.017, 1.002 ± 0.014, and 1.003 ± 0.01, respectively. Since the ratios are based on a 5 nm running mean, no information on small wavelength differences between the instruments can be obtained from these ratios. Spectral features of the order of 3–5% can be observed between the various instruments. The largest differences of 4–5% above 330 nm are seen with the SOLSPEC spectrum, while the largest difference to the mean UARS and ATLAS-1 spectrum are below 3% above 305 nm. This agreement between the BREWER solar spectrum and the space-based solar spectra shows the high accuracy achievable from the ground since differences of the same magnitude or larger are also observed between the various space-based spectra [*DeLand and Cebula*, 1998]. The 2–4% irradiance decrease below 305 nm is probably a feature of the BREWER spectrum and reflects the difficulties in determining the solar extraterrestrial irradiance in the presence of ozone which absorbs more than 99% of the incoming solar irradiance.

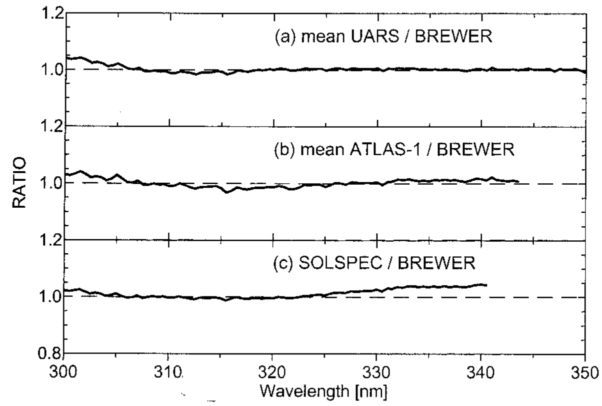

Figure 5. Ratios between 300 and 350 nm for the mean UARS, ATLAS 1, and SOLSPEC solar spectra relative to the BREWER spectrum. The ratios have been smoothed by a 5 nm running mean filter.

3.5. Comparison With ATLAS-3 Spectrum

During the last few years, the high-resolution solar spectrum from the ATLAS-3 mission obtained on November 13, 1994, has been increasingly used as reference in comparisons between radiative transfer calculations and ground measurements of the solar irradiance. We present here a comparison between the BREWER spectrum and this high-resolution spectrum.

3.5.1. Vacuum wavelengths. Before these two spectra can be compared, it is necessary to bring both spectra on the same wavelength scale since the ATLAS-3 spectrum is based on vacuum wavelengths and the scale of Brewer instruments is based on wavelengths in air at 1 atmosphere pressure. The relation between air and vacuum wavelengths is linear in wavelength and to the first order can be approximated by a wavelength shift of −0.1 nm around 350 nm when changing from vacuum to air wavelengths. Here we have also taken into account the gradient of the relation and applying it to the wavelengths of the ATLAS-3 spectrum, the wavelengths in air are obtained by shifting the vacuum wavelengths by −0.0850 nm at 290 nm to −0.1014 nm at 355 nm.

3.5.2. Slit resolution. The ATLAS-3 spectrum was measured with a slit resolution of 0.15 nm and at wavelength increments of 0.05 nm. Since Brewer 119 has a 4 times larger slit resolution (0.55 nm), it is necessary to convolve the ATLAS-3 spectrum with this wider slit function to compare both spectra. For this convolution the finite slit resolution of the ATLAS-3 instrument was neglected, which is acceptable considering the large difference in slit resolution between the two instruments. The convolution was performed over the wavelength range 290–355 nm using the ATLAS-3 spectrum shifted to air wavelengths and using the varying slit function of the Brewer. As mentioned before, the Brewer slit function varies linearly from 0.59 nm at 290 nm to 0.51 nm at 350 nm.

Figure 6 shows the ratio between the convolved ATLAS-3 spectrum and the BREWER spectrum. The uncertainty of the latter is shown by the two dashed lines and is taken from Table 1.

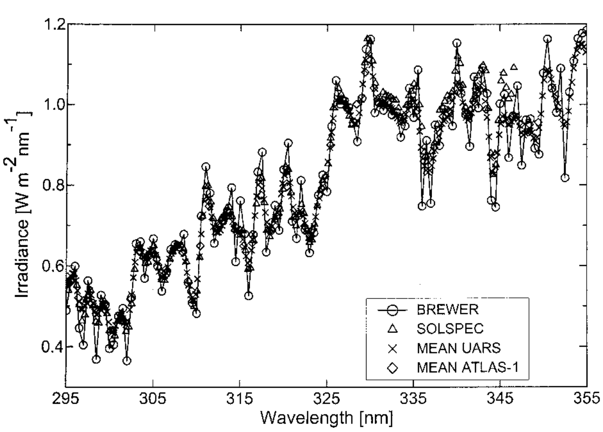

Figure 4. Spectral solar irradiance from 295 to 355 nm as measured by Brewer 119 and the mean UARS, ATLAS 1, and SOLSPEC spectra. The wavelengths are given for a standard atmosphere.

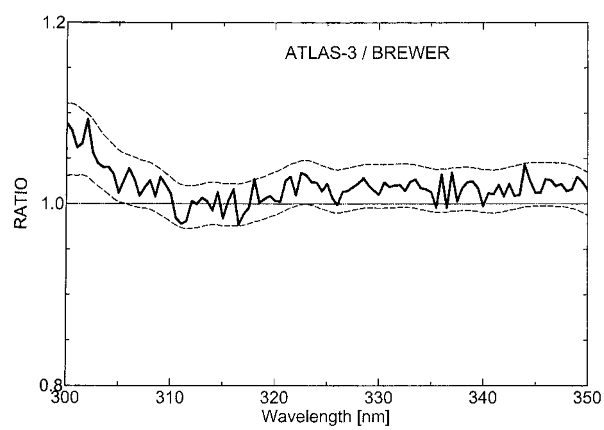

Figure 6. Ratio between the space-based ATLAS-3 spectrum and the BREWER spectrum. The average ratio is 1.017 with a standard deviation of ±1.5%. The uncertainty of the Brewer extraterrestrial spectrum is shown by the two dashed lines obtained by smoothing the ratio with a 3 nm wide triangular function.

The overall absolute agreement between the two spectra is satisfactory with a mean ratio of 1.017 between the ATLAS-3 spectrum and the BREWER spectrum. The remaining structure is of the order of ±1.5% and is defined as the root-mean-square departure from this average ratio of 1.017. We have assumed here that measurements at individual wavelengths are uncorrelated, which is consistent with the methodology used here. The largest structure above 305 nm is seen between 310 and 315 nm where the ATLAS-3 spectrum is about 2% lower than the average. The remaining wavelength-to-wavelength fluctuations are a product of the highly structured solar spectrum and of the measurements by instruments with different resolutions and possible wavelengths misalignments. Even wavelength differences as small as 0.01 nm between the instruments can produce noise dependent on wavelength of the order of 5%. Thus the average noise of 1.5% seen here shows that the wavelength scales of both instruments agree quite well over the whole wavelength range. It should be noted that our estimate for the wavelength-to-wavelength scatter, which we totally attribute to differences in wavelength setting or resolution, is an upper limit, since we define it as relative to a constant in wavelength. If we would be using a running mean to allow for a slowly varying reference curve, the noise is somewhat lower. As an example, using a 10 nm wide averaging filter, the noise relative to this curve is only 1%. Below 305 nm the BREWER spectrum and the ATLAS-3 spectrum show similar differences of about 5% as observed in the comparisons with the mean UARS and ATLAS-1 solar spectra shown in Figure 5.

4. Conclusion

Measurements of the solar extraterrestrial spectrum were carried out at Mauna Loa Observatory in Hawaii using a double Brewer spectrophotometer. Using 449 half days of measurements obtained between January 1 and October 2, 1998, an average solar extraterrestrial spectrum is constructed using a subset of 181 half days by applying a Langley regression to each half day. The fact that there was no significant seasonal variation observed in the record of 181 good quality extrapolated values made over the 9 month period is an important result. This indicates that any possible seasonal effects (e.g., temperature, Sun angle, ozone amount, diurnal variation, etc.) on the Langley extrapolation process at Mauna Loa are negligible. It also demonstrates the stability of the instrument over several months. Mauna Loa is the site used for zero air mass calibrations of Dobson [*Komhyr et al*., 1989] and Brewer [*Kerr et al*., 1998] ozone spectrophotometers and the seasonal stability of the extrapolated values at 300 nm (a wavelength strongly influenced by ozone variations) verifies that the calibrations can be carried out at any time of the year.

The accuracy of the BREWER spectrum of ±2.3% above 305 nm is comparable to the accuracy of measurements obtained by space-based instruments. Above 305 nm, differences below 3% are found between the BREWER spectrum and either the mean UARS or the mean ATLAS-1 spectrum, while larger differences are found with the SOLSPEC spectrum. This good agreement demonstrates the high accuracy achievable by the methodology presented here which can be used for a continuous quality assessment of ground-based absolute irradiance measurements, provided the conditions for accurate Langley extrapolations are fulfilled. Below 305 nm there remain some discrepancies between the BREWER spectrum and the space-based spectra of 2–4% which are however well within the uncertainties of the ground-based spectrum due to the large ozone absorption at these short wavelengths. The high-resolution ATLAS-3 spectrum as currently used has a 1.7% offset relative to the other solar spectra. By taking this offset into account, the high-resolution ATLAS-3 spectrum can be used as an accurate input parameter into radiative transfer calculations and thus answers some of the concerns mentioned by *Zeng et al*. [1994] and *Mayer and Seckmeyer* [1997].

A limitation of the measurements presented here is the relatively coarse wavelength sampling of 0.5 nm compared to the resolution of the spectrophotometer of about 0.55 nm. Future measurements will use higher sampling rates to allow postcorrections of possible wavelength misalignments and also to obtain an extraterrestrial value at any chosen wavelength in the measured wavelength interval.

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