



RESEARCH ARTICLE

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Monte Carlo Evaluation of Uncertainties of UV Spectra Measured With Brewer Spectroradiometers

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Key Points:

- A Monte Carlo technique has been implemented to obtain the uncertainty of the spectral ultraviolet recorded by a Brewer MKIII spectrometer
- The methodology used for the uncertainty propagation is general and can be adapted to most spectroradiometers used in ultraviolet (UV) research
- Brewer spectrometers are suitable for model and satellite validation but might be limited in the determination of spectral UV trends

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Abstract Precise spectral ultraviolet (UV) measurements are needed to ensure human protection as well as to support scientific research. Quantifying the uncertainty of the UV spectra recorded is crucial to evaluate the quality of the measurements which is needed, in turn, for the assessment of their reliability. However, for double-monochromator spectroradiometers, the analytical derivation of this uncertainty is a challenging task due to the difficulties involved in propagating individual uncertainties. Under these circumstances, a Monte Carlo simulation is a reliable alternative as it does not require the calculation of partial derivatives and considers both nonlinear effects and correlations in the data. In the present study, the uncertainty of the spectral UV irradiance measured by a Brewer MKIII spectrophotometer is evaluated using a Monte Carlo approach. This instrument belongs to the National Institute of Aerospace Technology and has successfully participated in several international campaigns, which ensures its precise calibration. The average expanded uncertainty ($k = 2$) of the global UV irradiance measured by this instrument varies between 10% at 300 nm and 7% at 363 nm. At shorter wavelengths, it increases sharply due to thermal and electronic noise as well as wavelength misalignment. The results indicate that a Brewer spectrophotometer is suitable for climatological studies and model validation. Nevertheless, a substantial reduction of these uncertainties might be required for accurately detecting long-term UV trends. Although the study focused on a Brewer spectrometer, the methodology used for the uncertainty analysis is general and can be adapted to most UV spectroradiometers.

Plain Language Summary The solar ultraviolet (UV) spectrum covers the wavelength range from 100 to 400 nm. Although it represents less than 10% of the total radiation reaching the earth's surface, it is of great importance as it can be harmful to humans, aquatic, and terrestrial ecosystems. To study its effects, high-quality measurements are needed. To determine the quality of the irradiance recorded its uncertainty must be first evaluated. Most techniques used for uncertainty estimation rely on the calculation of partial derivatives, which are difficult to obtain for most instruments measuring UV irradiance. The reason for this is that the mathematical expression relating some uncertainty sources and the measured irradiance is complex, with unknown correlations between the different uncertainty sources. To solve this problem, the Monte Carlo technique was used instead of the analytical one. The Monte Carlo approach is easier to implement and needs no calculation of partial derivatives. The method was implemented for a Brewer spectrometer, one of the preferred devices to measure UV irradiance. The results indicate that the Brewer is suitable for model validation, but a substantial reduction of its uncertainty might be needed to accurately detect spectral UV trends.

1. Introduction

The discovery of stratospheric ozone depletion over Antarctica and midlatitudes in the 1980s (Farman et al., 1985; Harris et al., 1997) stimulated the deployment of large ultraviolet radiation (UV) monitoring networks. Since ozone attenuates UV radiation, the widespread depletion resulted in a rise of surface UV levels, such as the increases reported by several stations during the 1990s (Kerr & McElroy, 1993; McKenzie et al., 1999; Seckmeyer et al., 1994; Zerefos et al., 1997). The regulation on ozone-depleting substances agreed in the Montreal Protocol decelerated the decrease in ozone levels (Morgenstern et al., 2008; Newman et al., 2009; Prather et al., 1996). Nevertheless, surface UV irradiance could still increase if its other influential factors, such as clouds or aerosols, vary.

Potential changes in solar UV irradiance are of great environmental concern as this radiation may have detrimental effects on humans (Bais et al., 2018; D'Orazio et al., 2013; Hart & Norval, 2018; Lumi et al., 2021), materials (Andrady et al., 2023; Wachter et al., 2021) as well as terrestrial and aquatic ecosystems (Barnes et al., 2023; García-Corral et al., 2020; Neale et al., 2023). Since these harmful effects depend greatly on the wavelength, spectral UV measurements are needed to accurately appraise their risks. Furthermore, continuous monitoring is also vital to assess the possible variations in surface UV levels due to the forecasted changes in clouds, aerosols, and surface reflectivity. However, providing reliable estimations of such trends is a challenging task as it requires low-uncertainty spectral measurements (Arola et al., 2003; Bernhard, 2011; Glandorf et al., 2005; Weatherhead et al., 1998). In fact, Bernhard and Seckmeyer (1999) found that even if the lowest possible uncertainty was assumed, around 2% for wavelengths below 320 nm, a double-monochromator spectroradiometer was unable to detect the change in erythemal UV due to a 1% change in ozone. Therefore, high-quality measurements are needed, with uncertainties lower than 2%.

To ensure low-uncertainty UV measurements, precise quality assurance (QA) and quality control (QC) procedures are essential. QA currently assesses the instrument's performance through intercomparison campaigns (e.g., Bais et al., 2001; Redondas et al., 2020). In particular, for solar UV measurements, the QASUME (Gröbner et al., 2005; Hülsen et al., 2016) acts as the traveling reference. Regarding QC, it is carried out at monitoring stations and includes identifying the uncertainty sources and evaluating the uncertainty of the measurements (Webb et al., 1998). Several studies have developed guides and recommendations to estimate UV irradiance uncertainty using the law of propagation of uncertainties (LPU) (Bernhard & Seckmeyer, 1999; Seckmeyer et al., 2001; Webb et al., 1998). Nonetheless, performing a complete evaluation of solar UV irradiance by applying LPU is highly complicated as it is difficult to provide the partial derivatives of the model used to derive the irradiance. Furthermore, it is unclear whether the uncertainty sources are correlated or if the model is linear. Under these circumstances, a Monte Carlo simulation is a reliable alternative as it does not require the calculation of partial derivatives and takes into account both nonlinear effects (BIPM et al., 2008) and correlations (Kärhä et al., 2017) in the spectral data.

The Monte Carlo approach has been used to evaluate the uncertainty of spectral irradiance measurements obtained from both double monochromator-based (Cordero, Seckmeyer, Pissulla, et al., 2008; Vaskuri et al., 2018) and CCD-array-based spectroradiometers (Cordero et al., 2012; Schinke et al., 2020; Schmähling et al., 2018). As for the Brewer spectrophotometer, this methodology was applied to estimate the uncertainty of its nitrogen dioxide measurements (Diémoz et al., 2014). Nonetheless, the uncertainty of its spectral UV irradiance measurements is yet to be studied, even though these instruments have greatly contributed to the establishment of worldwide UV monitoring networks. In fact, Brewer spectrophotometers have been performing global UV irradiance measurements since the 1990s, enabling the investigation of long-term UV changes (De Bock et al., 2014; Fioletov et al., 2001; Fountoulakis, Bais, et al., 2016; Lakkala et al., 2017; Zerefos et al., 2012). Moreover, their measurements have also been used to study biologically effective UV dose rates (Fioletov et al., 2003; Kimlin, 2004), to assess the influence of atmospheric constituents on UV radiation (Bernhard et al., 2007; Seckmeyer et al., 2008), and to validate radiative transfer models (Mayer et al., 1997). Thus, this instrument has significantly served the scientific community for more than 30 years.

In this paper, an uncertainty analysis of the spectral UV irradiance measured by a Brewer MKIII spectrometer has been carried out using a Monte Carlo-based uncertainty propagation technique. The spectral measurements used were performed after the XVI Intercomparison campaign of the Regional Brewer Calibration Center-Europe (RBCC-E) at National Institute of Aerospace Technology (INTA)/El Arenosillo.

The article is structured as follows. To begin with, Section 2 presents the technical characteristics of the double Brewer and its measuring procedure. Next, Section 3 describes the methodology as well as the characterization of the error sources considered in the analysis. Continuing with Section 4, where the Monte Carlo uncertainty evaluation is laid out. Finally, Section 5 summarizes the main conclusions.

2. Brewer MKIII Spectrophotometer

The Brewer MKIII spectrophotometer with serial number 150 (hereafter “Brewer #150”) is deployed at the “El Arenosillo” Atmospheric Sounding Station, belonging to the INTA. The Station is located in Mazagón, Huelva, Spain (37.1°N, 6.7°W, 41 m a.s.l.) and hosts, every 2 years, the RBCC-E calibration campaigns, where Brewers belonging to different institutions are calibrated for global UV irradiance and total ozone column.

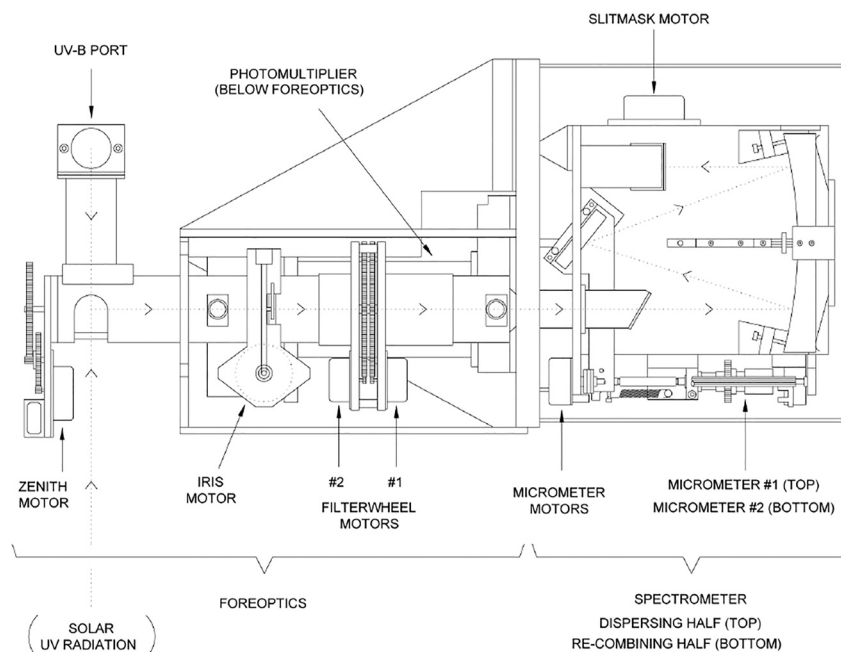


Figure 1. Top view of a Brewer MKIII spectrometer (Kipp and Zonen Brewer user manual).

The fully automated Brewer #150 is a double monochromator spectroradiometer manufactured by Kipp and Zonen (<https://www.kippzonen.com/>, last access: 22 December 2023), with headquarters in Delft, the Netherlands. It was installed at “El Arenosillo” in 1997 for the measuring of total ozone in column, aerosol optical depth, and solar spectral UV irradiance. Thanks to the quality of Brewer #150 spectral measurements, its UV data set has been used in many studies such as validation of satellite products (Antón et al., 2010; Cachorro et al., 2010), broadband calibration (Antón et al., 2011; Cancillo et al., 2005), and intercomparison campaigns (Cachorro et al., 2002).

For Brewer #150 spectral UV irradiance measurements, the wavelength range is 290–363 nm, with a step of 0.5 nm. It has a triangular slit function with a Full Width at Half Maximum of 0.55 nm. With these settings, the duration of a scan is approximately 4.5 min. The instrument is housed in a weather-proof box with no temperature stabilization.

To measure spectral UV irradiance, solar irradiance enters Brewer #150 through a CMS-Schreder entrance optic (model UV-J1015). It consists of a shaped Teflon diffuser covered by a quartz dome. This design is different from the standard entrance optic, a flat diffuser, and improves the Brewer angular response for global UV irradiance measurements (Gröbner, 2003). After passing through the diffuser, light is guided into the optical axis using a reflective prism. As seen in Figure 1, the light subsequently enters the fore-optics, which comprises a set of quartz lenses and an iris diaphragm to focus and collimate the beam, as well as two filter wheels. The first filter wheel contains one open hole, for UV measurements, and an opaque disk, for dark count tests. The second wheel has five neutral density filters to ensure the Brewer signal is within appropriate levels. Thereafter, radiation is focused onto the spectrometer. Brewer #150 spectrometer is a modified Ebert type consisting of a pair of monochromators and a slit mask placed in front of the exit slit plane. For the measuring of ozone, dead time, and dark counts, the slit mask rotates to select the wavelength, while the diffraction gratings remain fixed. On the other hand, for UV observations, the slits are fixed, and the wavelength is selected by rotating the gratings, using two micrometers. The incoming light is dispersed in the first monochromator and then recombined in the second one, reducing in this way the stray light of the system. Finally, the photons are collected on the cathode of a low-noise photomultiplier tube (PMT). The photon pulses are converted to counts per cycle. For Brewer measurements, the sampling time is performed in cycles, with the slit mask rotating in front of the exit slit plane of the spectrometer. In each position of the slotted mask, photons are allowed to reach the PMT during 0.1147 s which is called the integration time.

The output signal of the above measuring procedure is affected by several error sources and must be corrected before irradiance values can be derived. To convert the Brewer photon counts into irradiances, the responsivities of the instrument must be known. For Brewer #150, its spectral response is determined every year using several

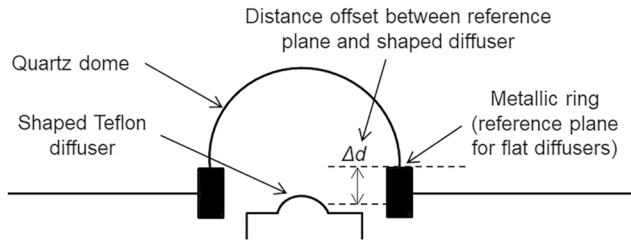


Figure 2. Schematic drawing of transversal cut of Brewer #150 curved diffuser.

quartz-halogen tungsten 1,000 W lamps with certified spectral irradiance. To prevent any changes in the instrument during transportation, the calibration is carried out using a mobile lamp system, placed on top of the instrument. The unit has three flat baffles, between the reference lamp and the entrance optics, to eliminate stray light. Furthermore, the whole system is covered by a black cloth to block external light. During the radiometric calibration, the current of the lamp is controlled and recorded to monitor its stability.

The model used to derive the irradiance measured by Brewer #150 will be explained in Sections 2.1 and 2.2. It is formed by a set of equations that relate the uncertainty sources (dead time, dark counts, temperature, etc.) to the final corrected irradiance. In the following, bold font will be used to represent spectral variables (vectors).

2.1. Radiometric Calibration

As mentioned earlier, the spectral responsivity \mathbf{R} of the Brewer is determined by irradiating the entrance optics with a reference lamp. To carry out the calibration, the distance between the lamp and the reference plane of the diffuser needs to be the one stated in the lamp's calibration certificate d_r . For the traditional design (a flat diffuser), this reference plane coincides with the metallic ring that surrounds the quartz dome (see Figure 2). However, Brewer #150 diffuser is placed below this reference. As a result, the distance d between the lamp and the diffuser must be adjusted to take into account this offset Δd (see Section 3.2.5)

$$d = d_r - \Delta d. \quad (1)$$

Once the distance is correctly adjusted and the lamp is stabilized, the photon counts L_0 are recorded in counts cycle⁻¹. The raw counts detected by the PMT are a sum of counts generated from UV photons as well as those arising from thermal noise, usually referred to as "dark counts" (see Section 3.2.3). Therefore, the raw counts L_0 must be corrected by subtracting the dark counts D_L . Regarding stray light, no correction is needed for a double Brewer (Bais et al., 1996), assuming that most of the stray light is rejected by the second spectrometer.

Following the algorithm set in Brewer's manual, the raw counts must be converted to count rates L_1 (counts s⁻¹). At each wavelength i , where $i = 290\text{--}363$ nm, the count rate is calculated as

$$L_{1,i} = \frac{2(L_{0,i} - D_L)}{C \cdot t}, \quad (2)$$

where t is the integration time and C is the number of cycles of the measurement. The integration time is 0.1147 s for all types of measurements while the number of cycles depends on the type of observation and wavelength. For lamp measurements, the number of cycles is 30 for wavelengths below 300 nm and 20 for wavelengths above 300 nm.

Next, the counts need to be corrected for nonlinearity. For Brewer spectrometers, the main cause of nonlinearity is the dead time τ (see Section 3.2.4), a time period where the photomultiplier is unable to detect any incoming photons. Assuming Poisson statistics, the corrected signal values L_2 are obtained in an iterative process ($n = 0 \dots 9$).

$$L_{2,i}(n+1) = L_{1,i} \cdot e^{L_{2,i}(n)\tau}, \quad (3)$$

where $L_{2,i}(0) = L_{1,i}$.

Finally, the spectral responsivity of the instrument \mathbf{R} can be obtained as

$$R_i = L_{2,i} / E_{L,i}, \quad (4)$$

where $E_{L,i}$ is the spectral irradiance emitted by the reference lamp.

2.2. Spectral Irradiance

To obtain solar irradiance measurements, Brewer #150 is placed outdoors and the raw counts under the Sun are measured S_0 . This signal might be affected by spikes, an unusual number of counts recorded that do not arise from the incident radiation. To detect and correct them, the methodology set by Meinander et al. (2003) has been

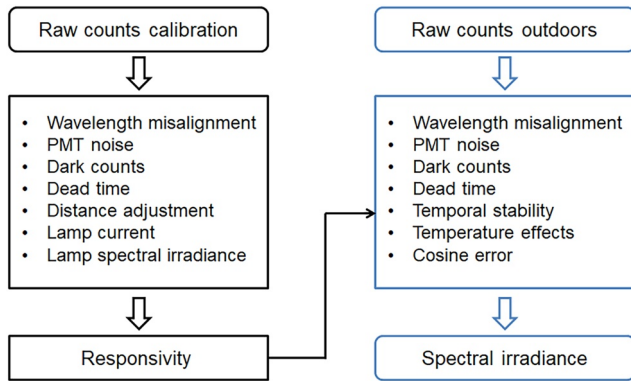


Figure 3. Schematic representation of the uncertainty sources affecting the spectral irradiance measured by Brewer #150. The left branch describes the uncertainties that affect the radiometric calibration and the right branch the ones involved in the field measurements.

applied. Furthermore, the outdoors signal values must also be corrected, similarly to the ones obtained during the calibration, for dark counts D , converted to count rate S_1 (in counts s^{-1}), and corrected for dead time S_2 (in counts s^{-1})

$$S_{1,i} = \frac{2(S_{0,i} - D)}{C \cdot t}, \quad (5)$$

$$S_{2,i}(n+1) = S_{1,i} \cdot e^{S_{2,i}(n) \cdot \tau}. \quad (6)$$

For UV observation, the number of cycles is different, four cycles for wavelengths below 300 nm and two cycles for wavelengths above 300 nm. Once the count rates are obtained, they are converted into spectral irradiance E_0 using the responsivity values of the instrument R , determined during the absolute calibration (as described in the previous section)

$$E_{0,i} = S_{2,i} / R_i. \quad (7)$$

Nevertheless, the spectral irradiance measured by a Brewer spectrometer needs further processing. As mentioned earlier, Brewer #150 has no temperature stabilization system. Consequently, its UV measurements have a linear dependence on temperature (see Section 3.2.9) and the irradiance values must be corrected E_1 using

$$E_{1,i} = E_{0,i} / (1 + c_t \cdot \Delta T), \quad (8)$$

where c_t is the temperature correction factor and ΔT is the difference between the reference temperature and the temperature of the scan.

Furthermore, the irradiances must also be corrected for its non-ideal angular response E_2 . Brewer #150 angular response was measured in the laboratory to obtain its cosine error at each wavelength. Once this error is determined, the spectral cosine correction function $A(SZA)$ can be simulated (see Section 3.2.10) and the irradiances are corrected by simply multiplying

$$E_{2,i} = E_{1,i} \cdot A_i. \quad (9)$$

3. Irradiance Uncertainty Analysis

3.1. Methodology

For the uncertainty evaluation, the measurements performed by Brewer #150 from 10 September to 20 October 2021 have been used. These measurements were obtained after a calibration took place, specifically during the XVI Intercomparison campaign of the RBCC-E (from 6 September to 15 September 2021) held at “El Arenosillo” Observatory. The study period was extended, until 20 October, to include the maximum number of cloud-free conditions possible. Cloudy conditions have not been considered since they strongly affect surface UV radiation (Schafer et al., 1996) and scanning spectrometers, such as Brewer #150, do not have enough temporal resolution to properly detect these fast changes. On the other hand, the study period could not be extended any further since, for later dates, the temperature of Brewer #150 was, for most UV scans, lower than 23°C, which is the limit of the temperature interval where its correction is characterized. Therefore, UV measurements recorded after 20 October 2021 have not been considered as their temperature dependence cannot be corrected. Putting the former criteria into practice resulted in 599 cloud-free UV spectra.

To determine the combined standard uncertainty of the spectral UV irradiance measured by Brewer #150, the methodology set in the Supplement 1 to the Guide to the Expression of Uncertainty in Measurement has been followed (BIPM et al., 2008). This consists of a Monte Carlo simulation that obtains the total uncertainty in three steps by identifying (a) the uncertainty sources affecting the measurements, (b) their probability density functions (PDFs), and (c) the measurement model that relates the spectral irradiance with the uncertainty sources (described in detail in Sections 2.1 and 2.2). The uncertainty sources for Brewer #150 are shown in Figure 3.

Their PDFs and how they affect the measurements will be discussed in the following Section 3.2. Once the three steps are completed, the spectral irradiance is calculated many times while varying the uncertainty sources according to their PDFs. For this study, the number of iterations was $N = 10^5$. The Monte Carlo simulation was implemented using two nested loops: one for the 10^5 Monte Carlo iterations and another one that goes through all the wavelengths (290–363 nm). If the uncertainty source depends on the wavelength (such as cosine error, PMT noise, or temporal stability), its values are drawn on the inner loop. In this way, the spectral sources are varied independently at each wavelength. On the other hand, if the uncertainty sources have no spectral dependency, such as dead time, dark counts, or temperature correction, they are varied on the outer loop. The simulation then renders a set of values of spectral irradiance $E_{S,1} \dots E_{S,N}$ that allows the calculation of the estimate E_M and their associated uncertainties u_M

$$E_M = \frac{1}{N} \sum_{j=1}^N E_{S,j}, \quad (10)$$

$$u_M = \left(\frac{1}{(N-1)} \sum_{j=1}^N (E_{S,j} - E_M)^2 \right)^{1/2}. \quad (11)$$

Moreover, the PDF of the spectral irradiance can also be obtained by calculating the histogram of $E_{S,j}$. If it is a normal distribution, the expanded uncertainties U_M can be obtained by multiplying the combined standard uncertainties with a coverage factor of $k = 2$.

3.2. Uncertainty Sources

This section describes the characterization and determination of the uncertainty sources used for the uncertainty analysis. Two main PDF have been considered: the rectangular and the Gaussian. The rectangular PDF is used for those variables that range within a certain interval of values without any preferred value. This is the case, for example, of wavelength misalignment due to the position of the micrometer. The step of this micrometer corresponds to 0.004 nm and, therefore, any wavelength within the micrometer position plus or minus 0.004 nm is equally possible. In this case, the rectangular PDF is the most suitable. On the other hand, there are variables with a clearly more probable value and an associated uncertainty that decreases as one departs from this more probable value. For these variables, a Gaussian PDF is more appropriate. An example of such a PDF is the number of dark counts. This number is estimated by measuring several times with the Brewer covered by a black cloth. The histogram of the resulting values shows a unimodal probability distribution that is adequately described by a Gaussian PDF. The mean and standard deviation are reliable estimates of the most likely value and the uncertainty of the distribution, respectively. The associated PDFs and their values are listed in Table 1.

3.2.1. Wavelength Misalignment

Due to ozone absorption the solar UV spectrum decreases sharply in the UVB region. As a result, small errors in the assigned wavelength of a spectrometer produce large deviations in its measured irradiance. To correct these wavelength misalignments a wavelength calibration must be performed before field measurements. This can be carried out by two methods: (a) comparing the wavelengths measured by the spectroradiometer against those corresponding to emission lines of several discharge lamps, such as mercury (Hg), cadmium (Cd), or zinc (Zn); (b) matching the Fraunhofer lines of the measured spectra with the respective ones in high-resolution reference spectra.

For Brewer #150, the wavelength calibration is carried out every 2 years following the procedures used by the RBCC-E (Gröbner et al., 1998; Kerr, 2002) at the calibration campaigns. In these procedures, the relation between the grating position and the actual wavelength of the monochromator is established by scanning spectral discharge lamps, usually Hg, Cd, and Zn. Furthermore, the resulting calibration is also checked using the Fraunhofer structure to determine wavelength shifts.

Table 1

Summary of the Probability Density Functions (PDFs) Assigned to the Different Uncertainty Sources Affecting the Brewer UV Irradiance Measurement

Uncertainty source	PDF
Wavelength misalignment (nm)	Described by two contributions: (1) Rectangular over the interval $(-0.004, 0.004)$ (2) Rectangular over the interval defined by the spectral shift
Signal noise (counts cycle ⁻¹)	Gaussian centered at the number of raw counts measured with standard deviations defined by the signal-to-noise-ratio
Dark counts (counts cycle ⁻¹)	Gaussian centered at dark counts measured with a constant standard deviation relative to the counts (40%)
Dead time (ns)	Gaussian centered at 26.7 with standard deviation 1.6
Distance adjustment (cm)	The uncertainty in the distance (50 cm) is described by two contributions: (1) Gaussian centered at 0 with standard deviation 0.015 (2) Rectangular over the interval $(-0.1, 0.1)$
Lamp current (A)	Rectangular over the interval $(7.999, 8.001)$
Lamp spectral irradiance (W m ⁻² nm ⁻¹)	Gaussian centered at E_L with the standard deviations indicated in the calibration certificate
Temporal stability (counts m ² nm s ⁻¹ W ⁻¹)	Gaussian centered at R with the standard deviations obtained from consecutive calibrations u_R
Temperature coefficient (% °C ⁻¹)	Gaussian centered at -0.156 with standard deviation 0.023
Cosine correction	Uniform distribution over the cosine corrections obtained with variable values of SZA, ozone, and aerosols

The standard uncertainty of this wavelength setting has two components: (a) the precision of the micrometer step setting and (b) the wavelength shifts. For Brewer spectrophotometers, the first contribution is approximately 8 p.m. (Gröbner et al., 1998). Therefore, according to the principle of maximum entropy (PME) (BIPM et al., 2008), the first component can be described by a rectangular distribution over the interval $(-0.004, 0.004)$ nm. As for the wavelength shifts, they can be derived from the wavelength calibration, either with discharge lamps or by comparison against the Fraunhofer structure. Similar wavelength shifts were found using the two methods, of the order of 0.01 nm at 300 nm. However, by matching the Fraunhofer lines, a specific spectral shift for each scan can be obtained. Therefore, shifts derived in this way were considered more accurate. Consequently, on each iteration, the wavelength scale was modified by

$$\lambda'_i = \lambda_i + u_w + z_i, \quad (12)$$

where λ_i are the wavelengths measured by Brewer #150 (290–363 nm), u_w is described by a rectangular PDF over the interval $(-0.004, 0.004)$ nm, and z_i is a rectangular distribution over the interval limited by the spectral shift for each wavelength. Spectral shifts were derived using the SHICRivm software package V. 3.075 (Slaper et al., 1995).

3.2.2. PMT Noise

Due to noise in the spectroradiometer signal, repeated measurements of the same irradiance level will lead to slightly different results. For Brewer spectrophotometers, this noise mainly arises from the quantized nature of the electrons produced in the PMT's cathode. Therefore, the raw counts measured by Brewer #150, both during the calibration L_0 and outdoors S_0 , are affected by this noise.

To characterize Brewer #150 noise during the calibration, the recommendations stated in Bernhard and Seckmeyer (1999) were followed, that is, the signal-to-noise-ratio (S/N) was derived from consecutive measurements of a 1,000 W lamp. For solar measurements, S/N is hard to accurately determine, as it depends on wavelength, SZA, and atmospheric variability. Nevertheless, an upper limit was estimated from a group of near measurements at each wavelength. The S/N measured, both during the calibration and measurements outdoors, decreases rapidly as wavelength increases. For the 310–360 nm wavelength region, it levels off at 3% and 0.11% for the 1,000 W lamp and field measurements, respectively.

To simulate the PMT noise, the raw counts measured by the Brewer were modified on each iteration by sampling from a normal distribution centered at the raw counts recorded with standard deviations defined by the S/N.

3.2.3. Dark Counts

Dark counts are measured automatically by setting the rotating slit mask at position 1, blocking all the slits and, in turn, blocking all incoming light. They are recorded before each UV scan. Since Brewer #150 is not stabilized in temperature, dark counts fluctuate throughout the day.

To characterize the dark counts measured by Brewer #150, the instrument was covered with a black cloth and performed 10 UV scans at 30°C. The results showed no spectral dependency. To estimate an uncertainty for the obtained dark counts of 0.5 counts per cycle, a standard deviation for the 10 scans performed was calculated. This standard deviation, 0.2 counts per cycle, represented 40% of the dark counts measured. Therefore, on each Monte Carlo iteration, the dark current was described by a normal PDF centered at the dark counts measured with a constant standard deviation relative to the counts (40%), in an attempt to simulate the effect temperature has on dark counts. Although the uncertainty evaluation is more precise in this way, introducing the temperature effects has no considerable impact on the total uncertainty budget. After varying the dark counts, the Brewer signal was corrected as indicated in Equations 2 and 5.

3.2.4. Dead Time

The cause of nonlinearity in Brewer spectrophotometers is the loss of photons due to the dead time τ of the photomultiplier. This constant is a measure of how long the detection system is “dead,” that is, it is the time after detecting a photon during which the PMT is unable to detect a second one. It is specific for each instrument as its value depends on the configuration and type of PMT used.

Brewer spectrophotometers can measure their dead time automatically by comparing the count rates when two slits are opened simultaneously to the counts registered when the slits are opened individually. A complete description of the algorithm used to derive the dead time and its calculation can be found in Fountoulakis, Redondas, et al. (2016).

Brewer #150 measures its dead time every day by performing a DT test. This test determines the dead time several times for high and low intensities of the internal standard lamp. Then, the mean and standard deviation are recorded in a file for both high- and low-intensity cases. According to the Brewer’s manual both measurements should agree within two standard deviations and lie in the range 20–35 ns. For the period of study, the mean dead time was 26.7 ns and its standard uncertainty 1.6 ns. If only high-intensity cases are considered, then the standard uncertainty of the dead time is 0.9 ns, in agreement with the findings of Fountoulakis, Redondas, et al. (2016).

In the Monte Carlo simulation, the DT is modified on each iteration by sampling from a Gaussian distribution centered at 26.7 ns with standard deviation of 1.6 ns. Once the DT is determined, the Brewer count rates, L_1 and S_1 , were corrected for nonlinearity using Equations 3 and 6.

3.2.5. Distance Adjustment

During the calibration, the response values of the spectroradiometer are obtained using the spectral irradiance of the lamp, as indicated in Equation 4. However, to ensure the lamp is emitting those irradiance values the distance between the reference lamp and the optical plane of the diffuser must be the one stated in the calibration certificate. Consequently, errors committed in this distance adjustment will lead to systematic errors in the measurements (Gröbner & Blumthaler, 2007; Hovila et al., 2005; Manninen et al., 2006).

As shown in Figure 2, Brewer #150 diffuser is placed below the used reference for calibration. To estimate the actual height of the diffuser, the spectrum emitted by an ultrastabilized lamp was measured at several distances. The results showed that the reference plane of the diffuser is situated $\Delta d = (0.234 \pm 0.015)$ cm below the metallic ring of the quartz dome. Therefore, Brewer #150 calibration needs to be performed by placing the reference lamp 0.23 cm below the distance specified in its calibration certificate. For 1,000 W lamps, this distance is 49.766 cm.

In the Monte Carlo simulation, the standard uncertainty committed in the distance adjustment has two components: (a) the precision of the instrument used (e.g., a ruler, a micrometer gauge) for measuring the distance and (b) the standard uncertainty of the offset Δd previously measured. For Brewer #150, the first contribution is described by a rectangular distribution over the interval $(-0.1, 0.1)$ cm. It is to note that this source of uncertainty could be easily improved by acquiring a more precise ruler or micrometer gauge. The second one can be described by a Gaussian distribution centered at 0 cm with standard deviation 0.015 cm, as obtained experimentally. It should be noticed that since the distance offset is modified, the distance between the lamp and the diffuser is no longer the one stated in the calibration certificate. Accordingly, the spectral irradiance changes and must be corrected using the inverse square law

$$E'_{L,i} = E_{L,i} \left(\frac{d_r}{d_r + u_d} \right)^2, \quad (13)$$

where $E'_{L,i}$ are the calculated irradiances of the reference lamp, d_r is the reference distance (for 1,000 W lamps is 50 cm) and u_d is the combined standard uncertainty of the offset obtained by adding the two components previously described.

Equation 13 is only valid if the distance between the lamp and the diffuser is sufficiently large. In the Monte Carlo simulation, the distance varies between 49.8 and 50.2 cm. Therefore, the lamp can still be regarded as a point source and Equation 13 holds.

3.2.6. Lamp Current

During the radiometric calibration, the reference lamp must be operated at the current specified in its calibration certificate. Maintaining constant the lamp current is essential since any deviations will lead to different spectral irradiance values than those stated in the lamp's calibration certificate (Webb et al., 1994).

According to Schinke et al. (2020), the variation in spectral irradiance due to changes in the operating current can be estimated by modeling the lamp as a black body radiator whose temperature is obtained from the following linear approximation

$$R(T) = R_0(1 + \alpha(T - T_0)), \quad (14)$$

where $R(T)$ is the resistance of the lamp's filament at the operating temperature, R_0 is the resistance at room temperature T_0 , and α denotes the temperature coefficient of the filament. The resistance at operating temperature can be easily derived since the lamp voltage and current are monitored throughout the whole calibration process. For Brewer #150 setup, the mean resistance is $R(T) = 14.26 \Omega$. On the other hand, the resistance and room temperature were measured before the calibration took place, obtaining a room temperature of $T_0 = 300.5 \text{ K}$ and a corresponding resistance of $R_0 = 0.89 \Omega$. Regarding the temperature coefficient α , it was derived in the laboratory by varying the lamp current at six different fixed values, from 6 to 8 A, and measuring, at each current level, the spectral irradiance emitted by the lamp 10 times. For each current value, the temperature of the lamp was estimated using Planck's law and the resistance was determined thanks to the monitored current and voltage values. The data showed that the lamp resistance depends linearly on the temperature with a slope of $\alpha = (0.00544 \pm 0.00014) \text{ K}^{-1}$. Introducing the previous values in Equation 14 the 1,000 W lamp was modeled as a black body with temperature 3,089 K.

In the Monte Carlo simulation, the current was slightly modified on each iteration, varying in turn the spectral irradiance of the lamp (as described in Schinke et al., 2020). The setup used for Brewer #150 calibration maintains the current constant at 8 A with an error of 1 mA. Therefore, according to the PME, the lamp current can be described by a rectangular PDF over the interval (7.999, 8.001) A.

3.2.7. Lamp Spectral Irradiance

The uncertainties of the spectral irradiance values emitted by the calibrating lamp E_L must be considered in the uncertainty analysis. For the 1,000 W lamp used in this study, the uncertainty values u_L are specified in the calibration certificate and range from 1.74% at 250 nm to 0.91% at 450 nm. Since they correspond to a coverage factor of $k = 2$, the spectral irradiance of the reference lamp was described by a normal PDF centered at E_L with standard deviations $u_L/2$.

3.2.8. Temporal Stability

The responsivity of a spectroradiometer changes with time due to the aging of the instrument, mechanical instabilities arising from its transportation or storage, among other factors. Consequently, consecutive calibrations result in different values of responsivity. To characterize the drifts of Brewer #150, the calibration records from 2005 to 2021 have been analyzed. No data from prior years have been considered since in 2005 the traditional entrance optic was replaced for the CMS-Schreder design, greatly affecting the response of the instrument.

As suggested in Bernhard and Seckmeyer (1999), the difference between consecutive calibrations has been obtained for every wavelength. The data was consistent with a normal distribution. Therefore, for each wavelength, a standard deviation $u_{R,i}$ was derived. For Brewer #150 these uncertainties range from 3.75% at 290 nm

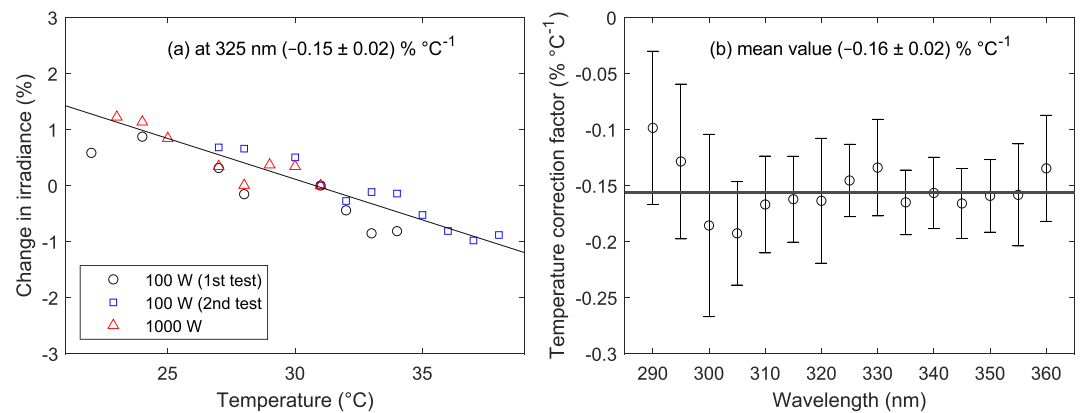


Figure 4. Results of the characterization in temperature for Brewer #150. (a) Change in irradiance (in %) at 325 nm with respect to the irradiance at 31°C as a function of the Brewer's internal temperature. Measurements were performed outdoors using 100 and 1,000 W lamps on three different days. (b) Wavelength dependence of the temperature correction, derived from linear fits.

to 3.24% at 363 nm. On each iteration, the responsivity of Brewer #150 was altered by sampling a Gaussian distribution centered at R with standard deviations u_R .

3.2.9. Temperature

Brewer spectrophotometers have no temperature stabilization system and therefore, their responsivity, and in turn their global UV measurements, depend on temperature (Cappellani & Kochler, 2000; Garane et al., 2006; Lakkala et al., 2008). For Brewer MKIII spectrometers, this sensitivity could be due to the effects temperature has on the PMT response as well as on the Teflon diffuser transmittance (Ylianttila & Schreder, 2005).

The temperature dependence is characteristic of each instrument (Fountoulakis et al., 2017; Weatherhead et al., 2001) and needs to be corrected. However, there is no standard methodology to characterize or correct the Brewer UV measurements. Existing studies have tried to characterize this dependence by using different external lamps (50, 200, and 1,000 W) and performing the measurements either outdoors (e.g., Cappellani & Kochler, 2000; Weatherhead et al., 2001) or inside a laboratory (e.g., Garane et al., 2006; Lakkala et al., 2008). Using the internal standard lamp of the Brewer may also lead to an unreliable characterization since the temperature dependence of this lamp is unknown (Weatherhead et al., 2001). Furthermore, in a recent study, Fountoulakis et al. (2017) found that 50 W lamps are also unsuitable for a thorough characterization as they are placed near the diffuser, affecting its temperature and eventually its performance. On the other hand, 200 and 1,000 W lamps provided reliable results since their distance from the diffuser was long enough to prevent its warming.

Brewer #150 was characterized using a 100 W lamp, placed at 10 cm from the diffuser. To guarantee that the diffuser was not being heated by this external lamp, the test was repeated with a 1,000 W lamp, placed at 50 cm of the diffuser. The measurements were performed outdoors while the internal temperature of the Brewer increased gradually as the Sun heated the instrument. During the scans, the current of the lamps remained stabilized to their operating current (8 A for the 1,000 W lamp and 6.6 A for the 100 W lamp). Furthermore, before each scan, the 297 nm line of the internal Hg lamp was scanned to ensure wavelength stability. This characterization test was repeated on three different days, two with the 100 W lamp and the remaining day with the 1,000 W lamp.

Using the temperature of the PMT, which is recorded by the Brewer during each scan, the change of the Brewer #150 responsivity with respect to temperature has been calculated. The data showed that the response of Brewer #150 decreases linearly with temperature and that the results were consistent for the three different experiments performed. Indicative results for 325 nm are presented in Figure 4. The temperature range measured was 23°C–38°C.

It can be seen from Figure 4 that the temperature correction factor for Brewer #150 shows no spectral dependency. Thus, the average value (-0.156 ± 0.023)% °C⁻¹, was chosen as the temperature correction factor for all the wavelength range. This value is similar to those obtained in previous studies (Fountoulakis et al., 2017; Garane et al., 2006; Weatherhead et al., 2001). Regarding the wavelength dependency, Garane et al. (2006) also obtained a correction factor with no spectral dependency. However, other studies have found a polynomial dependency

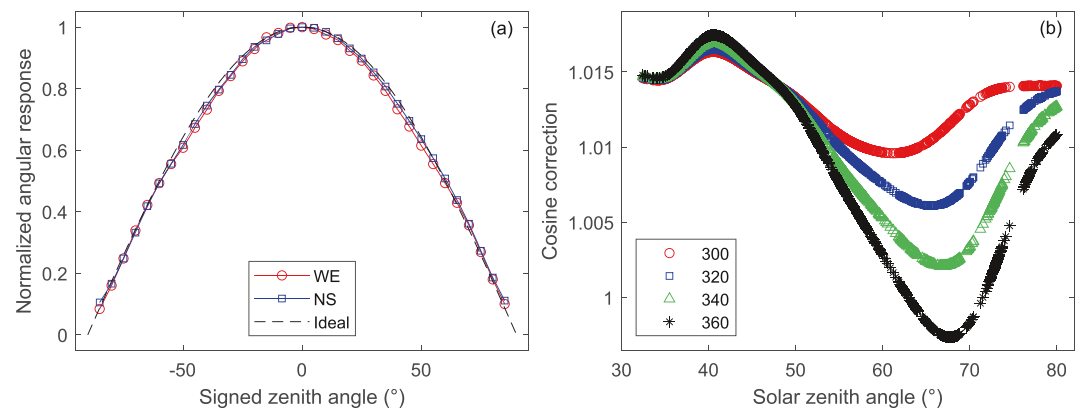


Figure 5. Cosine error characterization of Brewer #150. (a) Angular response measured for North-South and West-East planes and ideal response for different zenith angles at 315 nm. (b) Cosine correction for four wavelengths (300, 320, 340, and 360 nm) obtained for cloud-free skies and the mean values for columnar ozone and aerosols registered during the period of study.

for double monochromator Brewers (Fountoulakis et al., 2017; Lakkala et al., 2008). As already mentioned, the temperature dependence is characteristic of each Brewer and could be responsible for these differences.

Finally, in the Monte Carlo simulation, the temperature correction factor c_t is altered on each iteration by sampling from a normal distribution centered at $-0.156\% \text{ } ^\circ\text{C}^{-1}$ with standard deviation of $0.023\% \text{ } ^\circ\text{C}^{-1}$. Irradiance values are then corrected by applying Equation 8.

3.2.10. Cosine Error

The cosine error is the deviation from the ideal angular response. Ideally, the irradiance measurements of a spectroradiometer should be proportional to the cosine of the angle between the direction of the incoming radiation and the normal of the diffuser. Brewer #150 angular response was measured in the laboratory in October 2019 and is represented in Figure 5. To characterize the cosine error, the Brewer Angular Tester (BAT) device and a 150 W Xe arc lamp with an optic fiber were used.

The characterization was performed by placing the BAT device on top of the Brewer #150 diffuser. Once the lamp was stabilized, the angular response was measured at 315 nm for different zenith angles (starting from -85° to $+85^\circ$ by steps of 5°). Both orthogonal planes, North-South (NS) and West-East (WE) were measured twice. Using the angular response, the cosine error and its correction could be determined. The methodology followed was similar to the one described in Bais et al. (1998).

Calculating this correction accurately is a hard task since it requires modeling the direct-to-global ratio, for each scan measured, using simultaneous ancillary measurements of aerosol content, ozone, and surface albedo. Therefore, it is usual to perform the simulation with typical or mean values of these atmospheric parameters (e.g., Cordero, Seckmeyer, & Labbe, 2008; Fountoulakis et al., 2020). In this study, the influence of these assumptions will be analyzed. Consequently, in Equation 9 the cosine correction used is the one obtained with the mean values of ozone (287.5 DU) and aerosols (1.371 and 0.039 alpha and beta Ångström exponents, respectively) of the study period and is shown in Figure 5. On the other hand, the cosine correction was also calculated by modeling with simultaneous values of ozone and aerosols corresponding to each Brewer scan (variable parameters).

In the Monte Carlo simulation, the uncertainty of the cosine error will have two components: (a) the angular variability. A maximum error of 1° was estimated and (b) the error committed when ignoring the influence of aerosols and ozone in the model. Therefore, on each iteration, the cosine correction was obtained by sorting through the corrections calculated with atmospheric variable parameters and for the SZA of the corresponding scan $\pm 1^\circ$.

4. Monte Carlo Simulated Uncertainty

To analyze the combined standard uncertainty of Brewer #150 UV measurements, the standard deviations u_M were evaluated considering the irradiance model, uncertainty sources, and values reported in Section 3. The data used correspond to 599 UV spectra measured under cloud-free conditions. The average Brewer #150 irradiance

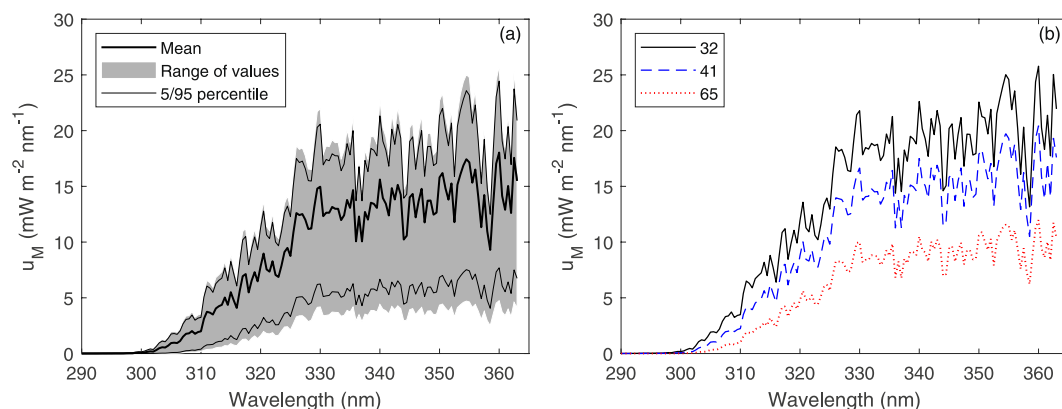


Figure 6. Combined standard uncertainty of Brewer #150 ultraviolet (UV) irradiance spectra. (a) Mean, range of values, and 5th and 95th percentiles of the ultraviolet (UV) irradiance combined standard uncertainty during the study period (from 10 September to 20 October 21). (b) Combined standard uncertainty of the UV irradiance measured on 10 September 2021 at three zenith angles: 32°, 41°, and 65°.

combined standard uncertainties for the wavelength range 290–363 nm as estimated by means of the Monte Carlo methodology are shown in Figure 6.

The combined standard uncertainty shows a marked spectral dependency, growing considerably with wavelength. Thus, its mean value ranges from 0.005 at 290 nm to 7.5 $\text{mW m}^{-2} \text{nm}^{-1}$ at 320 nm. This increase in the absolute value of the combined standard uncertainty was expected since it follows the shape of the global UV irradiance arriving at Earth's surface. The variability of the uncertainty can be described by the range between the 5th and 95th percentiles (Figure 6a). It rises gradually with wavelength until 320 nm, where it almost levels off. Its relative value exceeds 110% below 320 nm and around 90% hereafter.

The dependence of the combined standard uncertainty on solar angle was investigated by comparing its values for three different angles for the same date, 10 September 2021 (Figure 6b). The uncertainty is notably larger for low SZAs, with values for 32° doubling the values computed for 65° for wavelengths longer than 320 nm. In fact, the SZA is the most influential factor in determining the range of uncertainty values.

To illustrate the order of magnitude of the combined standard uncertainty compared to the solar irradiance spectra, an example scan is presented in Figure 7 alongside its uncertainty ($\pm 1\sigma$). Both linear and logarithmic scales are used to clarify the uncertainty contribution at short and large wavelengths.

Figure 7a shows that the absolute combined standard uncertainty is relatively small compared to the actual solar spectrum (around 4% for wavelengths above 310 nm). Due to the abrupt increase of solar irradiance with wavelength (four orders of magnitude), it may seem that the uncertainty is negligible at short wavelengths. However, if

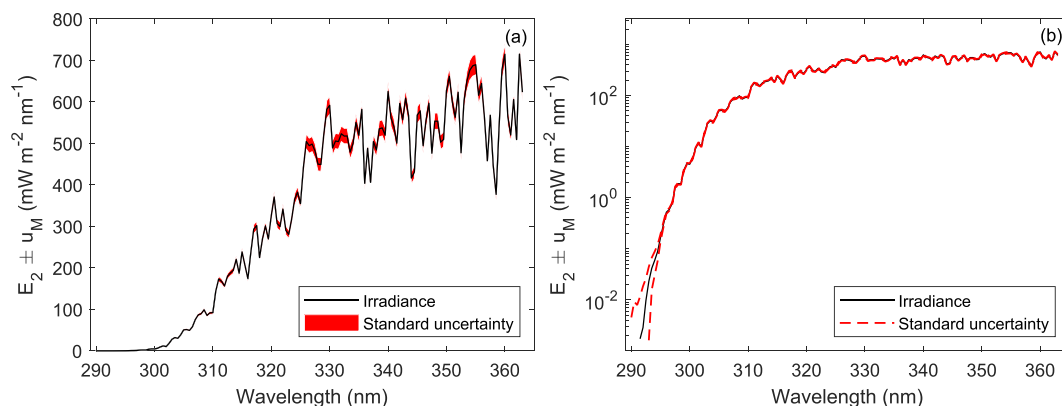


Figure 7. Solar irradiance and its combined standard uncertainty ($\pm 1\sigma$) for a spectrum measured on 10 September 2021 at a SZA of 32°C in (a) linear scale and (b) logarithmic scale.

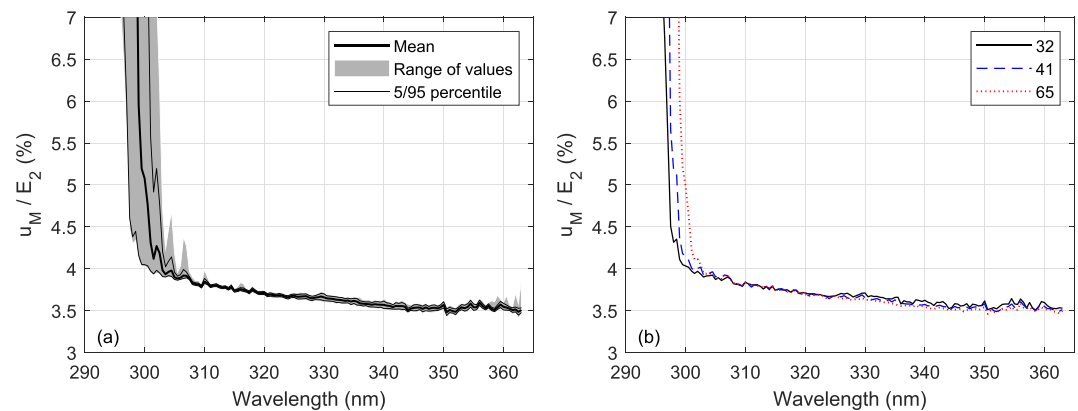


Figure 8. Relative combined standard uncertainty of the Brewer #150 ultraviolet (UV) irradiance spectra. (a) Range of values, mean, and 5th and 95th percentiles of the relative combined standard uncertainty during the study period. (b) Relative combined standard uncertainty of the UV irradiance measured on 10 September 2021 at three solar zenith angles: 32°, 41°, and 65°.

the same spectrum is represented in logarithmic scale (Figure 7b) it becomes visible that the combined standard uncertainty is large, exceeding 100% for wavelengths below 295 nm.

In addition to the absolute values of the combined standard uncertainty, the analysis of its relative values is of great interest due to the large variation of UV irradiance with wavelength. Thus, Figure 8 illustrates the relative values of the UV irradiance combined standard uncertainty, u_M/E_2 , with respect to the wavelength. For wavelengths below 300 nm, the average relative uncertainties exceed 100%. This mean value was expected since the irradiance comes close to zero as wavelength approaches 290 nm. For wavelengths above 300 nm, the mean relative combined standard uncertainty slowly decreases from 5.1% at 300 nm to 3.5% at 363 nm. Furthermore, some spikes can be observed at specific wavelengths such as 302, 304.5, or 306.5 nm (Figure 8a). They are caused by wavelength misalignment and have been already reported in other Monte Carlo simulations (Cordero, Seckmeyer, & Labbe, 2008; Schinke et al., 2020). Although they result in high uncertainties at the mentioned specific wavelengths, their effect on the average uncertainty is limited.

Regarding the variability, the 290–300 nm region shows the largest variability, of about 300%. This extremely high value is mainly produced by wavelength shift as well as PMT and thermal noise. These uncertainty sources have a greater effect for very low signals, which are recorded at short wavelengths and large SZAs. Their effect could be reduced by checking the wavelength alignment weekly or expanding the scan duration in an effort to decrease noise and instabilities. On the other hand, between 310 and 363 nm the uncertainty is independent of the SZA, and as a result the variability, defined as the difference between the 5th and the 95th percentiles, levels off at around 1.3%. This angular dependency agrees with the values reported by Bernhard and Seckmeyer (1999).

Furthermore, the main influences in the combined standard uncertainty can be studied by separating the contribution from the uncertainties committed during the calibration and the ones affecting the outdoors measurements (these uncertainty sources are shown in Figure 3). In this way, the dominant sources become visible.

Figure 9 shows the results of such calculation. The influence of the radiometric calibration is important for wavelengths larger than 305 nm. For this wavelength range (305–363 nm), the mean relative uncertainty (curve A) is 3.6% while the uncertainties arising from the radiometric calibration (curve B) and the outdoors measurements (curve C) are 3.4% and 0.5% respectively. The uncertainty source responsible for this effect is the stability of Brewer #150, ranging from 3.8% at 290 nm to 3.2% at 363 nm. Since the uncertainties arising from the calibration have no dependence on SZA, the relative combined standard uncertainty shows no significant angular dependence in this wavelength range. On the other hand, for wavelengths below 300 nm, the uncertainties arising from the measurements outdoors have the largest impact. This effect is due to PMT noise, dark counts, and wavelength misalignment. Furthermore, since the uncertainties from the outdoors measurements have a considerable angular dependence, the relative combined standard uncertainty shows the same dependence.

The spectral expanded uncertainty U_M can be obtained from the combined standard uncertainty multiplied by a coverage factor of $k = 2$. Therefore, the mean relative expanded uncertainty of Brewer #150 irradiance

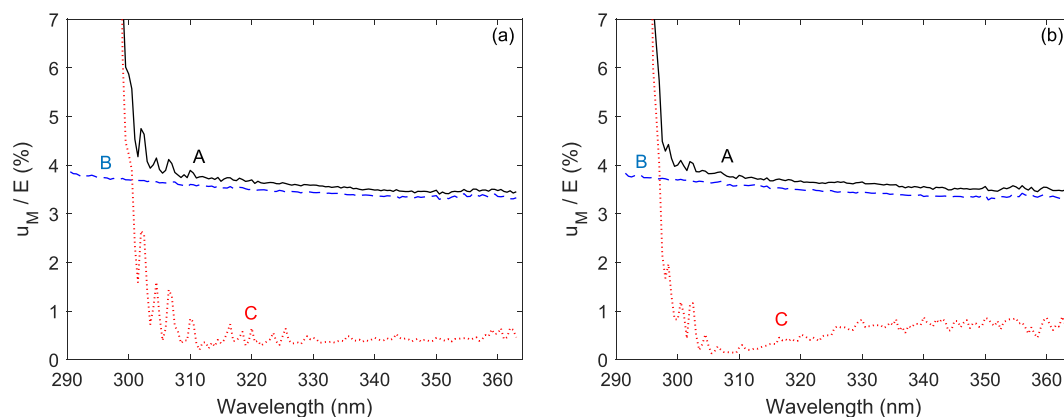


Figure 9. Contributions to the combined relative uncertainty of Brewer #150 ultraviolet irradiance measured on 10 September at a solar angle of (a) 65° and (b) 32°. Curve A depicts the combined relative uncertainty. Curves B and C show the contributions to the overall uncertainty depicted in curve A. The uncertainties in curve B were obtained considering only the uncertainty sources affecting the radiometric calibration. The uncertainties in curve C were calculated considering the uncertainty sources of the outdoors measurements.

measurements varies between 10% at 300 nm and 7% at 363 nm. Since the histogram of the spectral irradiance, as shown in Figure 10, is nearly a Gaussian distribution, the irradiance should lie in this interval with a probability of approximately 95%. The normality of the data was visually confirmed through a quantile-quantile plot.

Finally, the relative combined standard uncertainty of Brewer #150 can be compared with the one obtained in previous studies. Garane et al. (2006) used an MKIII Brewer and conducted an uncertainty analysis by applying the LPU. Their study reports a 1σ uncertainty of approximately 5% for the 290–363 nm range. This value is similar to the one obtained in our work at 300 nm. Furthermore, the shape of the spectral and angular dependency of Brewer #150 irradiance combined standard uncertainty is similar to the ones described in other publications (Bernhard & Seckmeyer, 1999; Gröbner et al., 2005). On the other hand, the expanded uncertainty of Brewer #150 can also be compared to the values reported in other studies for double monochromator spectroradiometers. Fountoulakis et al. (2020) used a Bentham DTM300 double monochromator and reported an expanded uncertainty at 300 nm of the order of 10%–12% for SZAs lower than 75°. Gröbner et al. (2005) conducted an uncertainty analysis for the QASUME and found an expanded uncertainty of 6.2% for the 310–400 nm range and SZAs lower than 50°. Therefore, Brewer #150 average expanded and relative combined standard uncertainty is comparable to those of other commercial double monochromators.

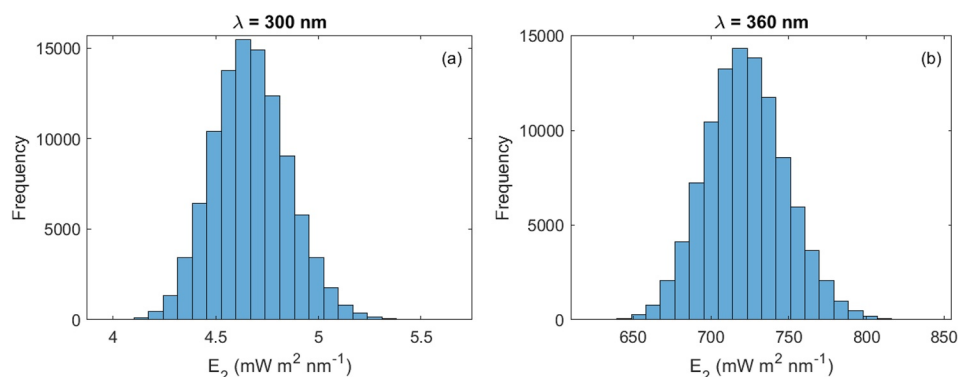


Figure 10. Histogram of the simulated irradiance at a solar zenith angle of 32° resulting from 10^5 iterations. (a) Global ultraviolet (UV) irradiance at 300 nm and (b) global UV irradiance at 360 nm. The expected values and standard deviations are (a) 4.67 and 0.18 $\text{mW m}^{-2} \text{nm}^{-1}$; (b) 722.50 and 25.69 $\text{mW m}^{-2} \text{nm}^{-1}$.

5. Conclusions

The combined standard uncertainty of Brewer #150 global UV spectra was obtained using a Monte Carlo uncertainty evaluation. The spectral measurements used were recorded from 10 September to 20 October 2021, after an absolute calibration was performed during the XVI Intercomparison Campaign of the RBCC-E. Only cloud-free conditions have been considered, resulting in 599 UV scans.

For the uncertainty evaluation, Brewer #150 was thoroughly characterized and its uncertainty sources studied in detail. In the Monte Carlo simulation, the effect of these uncertainty sources was considered by calculating the irradiance a large number of times ($N = 10^5$) while varying the uncertainty sources according to their assigned PDF.

Brewer #150 irradiance combined standard uncertainty depends significantly on wavelength and SZA, increasing as wavelength rises and SZA declines. Regarding the relative combined standard uncertainty, it also shows a considerable spectral dependency. For the 310–363 nm regions, it is mostly of the order of 3%–4%. In this wavelength range, the uncertainty is independent of solar zenith angle. In fact, the variability due to SZA is of the order of ~1%. The reason is that at this wavelength region the uncertainties arising from the radiometric calibration, in particular the stability, have the biggest impact. Since these uncertainty sources have no significant angular dependence, the relative uncertainty also shows no SZA dependency. However, for wavelengths below 310 nm, the relative combined standard uncertainty does depend significantly on SZA, decreasing as SZA increases. This is produced by three uncertainty sources whose effects affect mainly short wavelengths: PMT noise, dark counts, and wavelength shift.

The expanded uncertainty varies from 10% at 300 nm to 7% at 363 nm. Consequently, the UV data set of Brewer #150 is suitable for model and satellite validation as well as climatological studies. However, the determination of UV trends due to ozone change may be limited, as Brewer #150 combined standard uncertainty is higher than the change of erythral irradiance produced by a 1% change in ozone. Thus, work is needed to further reduce the uncertainty in order to accurately detect such trends. For Brewer #150, this could be achieved by improving its temporal stability.

Although a Brewer spectrophotometer was used in this work, the methodology employed to evaluate its uncertainty can be applied to other double monochromator instruments. Furthermore, it could be adapted for CCD-array spectroradiometers if their stray light is properly characterized and included in the uncertainty evaluation.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The dataset used for the uncertainty evaluation of Brewer #150 is available at Zenodo (González et al., 2023a). The software (version 1.0) associated with this manuscript for the implementation of the Monte Carlo method is published on Zenodo (González et al., 2023b). Ozone data measured by Brewer #150 was used in the creation of this manuscript and can be downloaded from EuBrewNet (Rimmer et al., 2018). Aerosol optical depth measured at INTA/El Arenosillo station was used for the cosine correction and can be downloaded from AERONET (Dubovik & King, 2000; Holben et al., 1998).

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