Monte-Carlo Evaluation of Uncertainties of UV Spectra Measured with Brewer Spectroradiometers

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- 10 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 UV research.
- Brewer spectrometers are suitable for model and satellite validation but might be limited
 in the determination of spectral UV trends.

17

18 Abstract

Precise spectral ultraviolet (UV) measurements are needed to ensure human protection as well as 19 20 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 21 reliability. However, for double-monochromator spectroradiometers, the analytical derivation of 22 this uncertainty is a challenging task due to the difficulties involved in propagating individual 23 uncertainties. Under these circumstances, a Monte Carlo simulation is a reliable alternative as it 24 does not require the calculation of partial derivatives and considers both nonlinear effects and 25 26 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. 27 28 This instrument belongs to the National Institute of Aerospace Technology and has successfully 29 participated in several international campaigns, which ensures its precise calibration. The 30 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 31 32 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. 33 Nevertheless, a substantial reduction of these uncertainties might be required for accurately 34 detecting long-term UV trends. Although the study focused on a Brewer spectrometer, the 35 methodology used for the uncertainty analysis is general and can be adapted to most UV 36 spectroradiometers. 37 **Plain Language Summary** 38

39 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 40 importance as it can be harmful to humans, aquatic, and terrestrial ecosystems. To study its 41 effects, high-quality measurements are needed. To determine the quality of the irradiance 42 recorded its uncertainty must be first evaluated. Most techniques used for uncertainty estimation 43 rely on the calculation of partial derivatives, which are difficult to obtain for most instruments 44 45 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 46 the different uncertainty sources. To solve this problem, the Monte Carlo technique was used 47 instead of the analytical one. The Monte Carlo approach is easier to implement and needs no 48 calculation of partial derivatives. The method was implemented for a Brewer spectrometer, one 49 of the preferred devices to measure UV irradiance. The results indicate that the Brewer is 50 suitable for model validation, but a substantial reduction of its uncertainty might be needed to 51 accurately detect spectral UV trends. 52

53 **1 Introduction**

54 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

56 (UV) monitoring networks. Since ozone attenuates UV radiation, the widespread depletion

57 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 63 have detrimental effects on humans (Bais et al., 2018; D'Orazio et al., 2013; Hart & Norval, 64 2018; Lumi et al., 2021), materials (Andrady et al., 2023; Wachter el al., 2021) as well as 65 terrestrial and aquatic ecosystems (Barnes et al., 2023; García-Corral et al., 2020; Neale et al., 66 2023). Since these harmful effects depend greatly on the wavelength, spectral UV measurements 67 are needed to accurately appraise their risks. Furthermore, continuous monitoring is also vital to 68 assess the possible variations in surface UV levels due to the forecasted changes in clouds, 69 70 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; 71 72 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 % 73 for wavelengths below 320 nm, a double-monochromator spectroradiometer was unable to detect 74 the change in erythemal UV due to a 1% change in ozone. Therefore, high-quality 75 measurements are needed, with uncertainties lower than 2 %. 76

To ensure low-uncertainty UV measurements, precise quality assurance (QA) and quality control 77 78 (QC) procedures are essential. QA currently assesses the instrument's performance through 79 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 80 81 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). 82 Several studies have developed guides and recommendations to estimate UV irradiance 83 uncertainty using the law of propagation of uncertainties (LPU) (Bernhard & Seckmeyer, 1999; 84 Seckmeyer et al., 2001; Webb et al., 1998). Nonetheless, performing a complete evaluation of 85 86 solar UV irradiance by applying LPU is highly complicated as it is difficult to provide the partial 87 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 88

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 92 93 measurements obtained from both double monochromator-based (Cordero et al., 2008b; Vaskuri et al., 2018) and CCD-array-based spectroradiometers (Cordero et al., 2012; Schinke et al., 2020; 94 Schmähling et al., 2018). As for the Brewer spectrophotometer, this methodology was applied to 95 estimate the uncertainty of its nitrogen dioxide measurements (Diémoz et al., 2014). 96 97 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 98 monitoring networks. In fact, Brewer spectrophotometers have been performing global UV 99 irradiance measurements since the 1990s, enabling the investigation of long-term UV changes 100 101 (De Bock et al., 2014; Fioletov et al., 2001; Fountoulakis et al., 2016a; Lakkala et al., 2017; 102 Zerefos et al., 2012). Moreover, their measurements have also been used to study biologically 103 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 104 validate radiative transfer models (Mayer et al., 1997). Thus, this instrument has significantly 105 served the scientific community for more than 30 years. 106

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 INTA / El Arenosillo.

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

116 **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 National Institute of Aerospace Technology (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 (TOC).

123 The fully-automated Brewer #150 is a double monochromator spectroradiometer manufactured by Kipp and Zonen (https://www.kippzonen.com/, last access: 7 June 2023), with headquarters in 124 Delft, the Netherlands. It was installed at "El Arenosillo" in 1997 for the measuring of total 125 ozone in column, aerosol optical depth, and solar spectral UV irradiance. Thanks to the quality 126 of Brewer #150 spectral measurements, its UV dataset has been used in many studies such as 127 validation of satellite products (Antón et al., 2010; Cachorro et al., 2010), broadband calibration 128 (Antón et al., 2011; Cancillo et al., 2005), and intercomparison campaigns (Cachorro et al., 129 2002). 130

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 (FWHM) 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.



135

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

137 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 138 quartz dome. This design is different from the standard entrance optic, a flat diffuser, and 139 improves the Brewer angular response for global UV irradiance measurements (Gröbner, 2003). 140 After passing through the diffuser, light is guided into the optical axis using a reflective prism. 141 As seen in Fig. 1, the light subsequently enters the fore-optics, which comprises a set of quartz 142 lenses and an iris diaphragm to focus and collimate the beam, as well as two filter wheels. The 143 first filter wheel contains one open hole, for UV measurements, and an opaque disk, for dark 144 count tests. The second wheel has five neutral density filters to ensure the Brewer signal is 145 within appropriate levels. Thereafter, radiation is focused onto the spectrometer. Brewer #150 146 spectrometer is a modified Ebert type consisting of a pair of monochromators and a slit mask 147 placed in front of the exit slit plane. For the measuring of ozone, dead time, and dark counts, the 148 149 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 150 the gratings, using two micrometers. The incoming light is dispersed in the first monochromator 151 and then recombined in the second one, reducing in this way the stray light of the system. 152 Finally, the photons are collected on the cathode of a low-noise photomultiplier tube (PMT). The 153

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.

158 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 159 irradiances, the responsivities of the instrument must be known. For Brewer #150, its spectral 160 161 response is determined every year using several quartz-halogen tungsten 1000 W lamps with 162 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 163 has three flat baffles, between the reference lamp and the entrance optics, to eliminate stray light. 164 Furthermore, the whole system is covered by a black cloth to block external light. During the 165 radiometric calibration, the current of the lamp is controlled and recorded to monitor its stability. 166

The model used to derive the irradiance measured by Brewer #150 will be explained in Sect. 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).

171 **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 Fig. 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 Sect. 3.2.5)

$$179 \quad d = d_{\rm r} - \Delta d \;. \tag{1}$$

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

- 183 counts" (see Sect. 3.2.3). Therefore, the raw counts L_0 must be corrected by subtracting the dark
- 184 counts $D_{\rm L}$. 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.



186

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

Following the algorithm set in Brewer's manual, the raw counts must be converted to count rates

189 L_1 (counts s⁻¹). At each wavelength *i*, where i = 290-363 nm, the count rate is calculated as

190
$$L_{1,i} = \frac{2(L_{0,i} - D_{\rm L})}{C \cdot t},$$
 (2)

where t is the integration time and C 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 non-linearity. For Brewer spectrometers, the main cause of nonlinearity is the dead time τ (see Sect. 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...9)

199
$$L_{2,i}(n+1) = L_{1,i} \cdot e^{L_{2,i}(n) \cdot \tau}$$
, (3)

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

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

202
$$R_i = L_{2,i} / E_{\mathrm{L},i}$$
, (4)

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

204 **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 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)

211
$$S_{1,i} = \frac{2(S_{0,i}-D)}{C \cdot t},$$
 (5)

212
$$S_{2,i}(n+1) = S_{1,i} \cdot e^{S_{2,i}(n) \cdot \tau}$$
 (6)

For UV observation, the number of cycles is different, 4 cycles for wavelengths below 300 nm and 2 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)

217
$$E_{0,i} = S_{2,i}/R_i$$
 (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 for temperature (see Sect. 3.2.9) and the irradiance values must be corrected E_1 using

222
$$E_{1,i} = E_{0,i} / (1 + c_t \cdot \Delta T),$$
 (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 Sect. 3.2.10) and the irradiances are corrected by simply multiplying

229
$$E_{2,i} = E_{1,i} \cdot A_i$$
. (9)

3 Irradiance uncertainty analysis

231 **3.1 Methodology**

For the uncertainty evaluation, the measurements performed by Brewer #150 from 10 September 232 to 20 October 2021 have been used. These measurements were obtained after a calibration took 233 place, specifically during the XVI Intercomparison campaign of the RBCC-E (from 6 September 234 to 15 September 2021) held at "El Arenosillo" Observatory. The study period was extended, 235 until 20 October, to include the maximum number of cloud-free conditions possible. Cloudy 236 conditions have not been considered since they strongly affect surface UV radiation (Schafer et 237 al., 1996) and scanning spectrometers, such as Brewer #150, do not have enough temporal 238 resolution to properly detect these fast changes. On the other hand, the study period could not be 239 extended any further since, for later dates, the temperature of Brewer #150 was, for most UV 240 scans, lower than 23 °C, which is the limit of the temperature interval where its correction is 241 characterised. Therefore, UV measurements recorded after 20 October 2021 have not been 242 considered as their temperature dependence cannot be corrected. Putting the former criteria into 243 practice resulted in 599 cloud-free UV spectra. 244



245

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.

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 (GUM) has been followed (BIPM et al., 2008). This consists of a Monte Carlo simulation that obtains the total uncertainty in three steps by identifying (1) the

uncertainty sources affecting the measurements, (2) their probability density functions (PDFs), 253 and (3) the measurement model that relates the spectral irradiance with the uncertainty sources 254 (described in detail in Sect. 2.1 and 2.2). The uncertainty sources for Brewer #150 are shown in 255 Fig. 3. Their PDFs and how they affect the measurements will be discussed in the following 256 Sect. 3.2. Once the three steps are completed, the spectral irradiance is calculated many times 257 while varying the uncertainty sources according to their PDFs. For this study, the number of 258 iterations was $N = 10^5$. The Monte Carlo simulation was implemented using two nested loops: 259 one for the 10⁵ Monte-Carlo iterations and another one that goes through all the wavelengths 260 (290–363 nm). If the uncertainty source depends on the wavelength (such as cosine error, PMT 261 noise or temporal stability), its values are drawn on the inner loop. In this way, the spectral 262 sources are varied independently at each wavelength. On the other hand, if the uncertainty 263 264 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 265 irradiance $E_{S,1}...E_{S,N}$ that allows the calculation of the estimate E_M and their associated 266 uncertainties $u_{\rm M}$ 267

268
$$\boldsymbol{E}_{M} = \frac{1}{N} \sum_{j=1}^{N} \boldsymbol{E}_{S,j} ,$$
 (10)

269
$$\boldsymbol{u}_{\mathrm{M}} = \left(\frac{1}{(N-1)}\sum_{j=1}^{N} \left(\boldsymbol{E}_{\mathrm{S},j} - \boldsymbol{E}_{\mathrm{M}}\right)^{2}\right)^{1/2}.$$
 (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 probability density functions (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 281 that decreases as one departs from this more probable value. For these variables, a Gaussian PDF 282 is more appropriate. An example of such a PDF is the number of dark counts. This number is 283 estimated by measuring several times with the Brewer covered by a black cloth. The histogram 284 of the resulting values shows a unimodal probability distribution that is adequately described by 285 a Gaussian PDF. The mean and standard deviation are reliable estimates of the most likely value 286 and the uncertainty of the distribution, respectively. The associated PDFs and their values are 287 listed in Table 1. 288

- 289
- 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 centred at the number of raw counts
	measured with standard deviations defined by the
	signal-to-noise-ratio
Dark counts (counts cycle ⁻¹)	Gaussian centred at dark counts measured with a
	constant standard deviation relative to the counts
	(40 %)
Dead time (ns)	Gaussian centred 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 centred 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 centred at $E_{\rm L}$ with the standard deviations
	indicated in the calibration certificate
Temporal stability (counts m ² nm s ⁻¹ W ⁻¹)	Gaussian centred at \boldsymbol{R} with the standard deviations
	obtained from consecutive calibrations $u_{\rm R}$
Temperature coefficient (% °C ⁻¹)	Gaussian centred 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

3.2.1 Wavelength misalignment

293 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 294 295 measured irradiance. To correct these wavelength misalignments a wavelength calibration must be performed before field measurements. This can be carried out by two methods: (1) comparing 296 297 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); (2) 298 299 matching the Fraunhofer lines of the measured spectra with the respective ones in highresolution reference spectra. 300

For Brewer #150, the wavelength calibration is carried out every two 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.

The standard uncertainty of this wavelength setting has two components: (1) the precision of the micrometer step setting and (2) the wavelength shifts. For Brewer spectrophotometers, the first contribution is approximately 8 pm (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

317
$$\lambda'_i = \lambda_i + u_w + z_i , \qquad (12)$$

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).

322 **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 characterise Brewer #150 noise during the calibration, the recommendations stated in 328 Bernhard and Seckmeyer (1999) were followed, i.e. the signal-to-noise-ratio S/N was derived 329 330 from consecutive measurements of a 1000 W lamp. For solar measurements, S/N is hard to accurately determine, as it depends on wavelength, SZA, and atmospheric variability. 331 Nevertheless, an upper limit was estimated from a group of near measurements at each 332 wavelength. The S/N measured, both during the calibration and measurements outdoors, 333 decreases rapidly as wavelength increases. For the 310-360 nm wavelength region, it levels off 334 at 3 % and 0.11 % for the 1000 W lamp and field measurements, respectively. 335

To simulate the PMT noise, the raw counts measured by the Brewer were modified on each iteration by sampling from a normal distribution centred at the raw counts recorded with standard deviations defined by the signal-to-noise-ratio.

339 **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 characterise the dark counts measured by Brewer #150, the instrument was covered with a 343 black cloth and performed ten UV scans at 30 °C. The results showed no spectral dependency. 344 To estimate an uncertainty for the obtained dark counts of 0.5 counts per cycle, a standard 345 deviation for the ten scans performed was calculated. This standard deviation, 0.2 counts per 346 347 cycle, represented 40 % of the dark counts measured. Therefore, on each Monte Carlo iteration, the dark current was described by a normal PDF centred at the dark counts measured with a 348 constant standard deviation relative to the counts (40%), in an attempt to simulate the effect 349 temperature has on dark counts Although the uncertainty evaluation is more precise in this way, 350 351 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 Eq. (2) and (5). 352

353 **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', i.e. 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 et al. (2016b).

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 et al.(2016b).

In the Monte Carlo simulation, the DT is modified on each iteration by sampling from a Gaussian distribution centred 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 Eq. (3) and (6).

375 **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 Eq. (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 Fig. 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 1000 W lamps this distance is 49.766 cm.

In the Monte Carlo simulation, the standard uncertainty committed in the distance adjustment has 388 two components: (1) the precision of the instrument used (e.g. a ruler, a micrometer gauge) for 389 measuring the distance and (2) the standard uncertainty of the offset Δd previously measured. For 390 Brewer #150, the first contribution is described by a rectangular distribution over the interval (-391 0.1, 0.1) cm. It is to note that this source of uncertainty could be easily improved by acquiring a 392 more precise ruler or micrometer gauge. The second one can be described by a gaussian 393 394 distribution centred 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 395 the diffuser is no longer the one stated in the calibration certificate. Accordingly, the spectral 396 irradiance changes and must be corrected using the inverse square law 397

398
$$E'_{\mathrm{L},i} = E_{\mathrm{L},i} \left(\frac{d_{\mathrm{r}}}{d_{\mathrm{r}} + u_{\mathrm{d}}} \right)^2,$$
 (13)

where $E'_{L,i}$ are the calculated irradiances of the reference lamp, d_r is the reference distance (for 1000 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 Eq. (13) holds.

405 **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 modelling the lamp as a black body radiator whose temperature is obtained from the following linear approximation

413
$$R(T) = R_0 (1 + \alpha (T - T_0)),$$
 (14)

414 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 415 resistance at operating temperature can be easily derived since the lamp voltage and current are 416 monitored throughout the whole calibration process. For Brewer #150 setup, the mean resistance 417 is $R(T) = 14.26 \Omega$. On the other hand, the resistance and room temperature were measured before 418 the calibration took place, obtaining a room temperature of $T_0 = 300.5$ K and a corresponding 419 resistance of $R_0 = 0.89 \Omega$. Regarding the temperature coefficient α , it was derived in the 420 laboratory by varying the lamp current at six different fixed values, from 6 to 8 A, and 421 measuring, at each current level, the spectral irradiance emitted by the lamp ten times. For each 422 current value, the temperature of the lamp was estimated using Planck's law and the resistance 423 was determined thanks to the monitored current and voltage values. The data showed that the 424 lamp resistance depends linearly on the temperature with a slope of $\alpha = (0.00544 \pm 0.00014) \text{ K}^{-1}$. 425

Introducing the previous values in Eq. (14) the 1000 W lamp was modeled as a black body with
temperature 3089 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.

433 **3.2.7 Lamp spectral irradiance**

The uncertainties of the spectral irradiance values emitted by the calibrating lamp $E_{\rm L}$ must be considered in the uncertainty analysis. For the 1000 W lamp used in this study, the uncertainty values $u_{\rm L}$ 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 $E_{\rm L}$ with standard deviations $u_{\rm L}/2$.

439 **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 characterise the drifts of Brewer #150, the calibration records from 2005 to 2021 have been analysed. 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.

446 As suggested in Bernhard and Seckmeyer (1999), the difference between consecutive 447 calibrations has been obtained for every wavelength. The data was consistent with a normal 448 distribution. Therefore, for each wavelength, a standard deviation $u_{R,i}$ was derived. For Brewer 449 #150 these uncertainties range from 3.75 % at 290 nm to 3.24 % at 363 nm. On each iteration, 450 the responsivity of Brewer #150 was altered by sampling a Gaussian distribution centred at *R* 451 with standard deviations u_R .

452 **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; 458 Weatherhead et al., 2001) and needs to be corrected. However, there is no standard methodology 459 460 to characterise or correct the Brewer UV measurements. Existing studies have tried to characterise this dependence by using different external lamps (50, 200, and 1000 W) and 461 performing the measurements either outdoors (e.g. Cappellani & Kochler, 2000; Weatherhead et 462 al., 2001) or inside a laboratory (e.g. Garane et al., 2006; Lakkala et al., 2008). Using the internal 463 standard lamp of the Brewer may also lead to an unreliable characterization since the 464 temperature dependence of this lamp is unknown (Weatherhead et al., 2001). Furthermore, in a 465 recent study, Fountoulakis et al. (2017) found that 50 W lamps are also unsuitable for a thorough 466 characterization as they are placed near the diffuser, affecting its temperature and eventually its 467 performance. On the other hand, 200 and 1000 W lamps provided reliable results since their 468 distance from the diffuser was long enough to prevent its warming. 469
- Brewer #150 was characterised using a 100 W lamp, placed at 10 cm from the diffuser. To 470 guarantee that the diffuser was not being heated by this external lamp, the test was repeated with 471 a 1000 W lamp, placed at 50 cm of the diffuser. The measurements were performed outdoors 472 while the internal temperature of the Brewer increased gradually as the Sun heated the 473 instrument. During the scans, the current of the lamps remained stabilized to their operating 474 current (8 A for the 1000 W lamp and 6.6 A for the 100 W lamp). Furthermore, before each scan, 475 the 297 nm line of the internal Hg lamp was scanned to ensure wavelength stability. This 476 characterization test was repeated on three different days, two with the 100 W lamp and the 477 remaining day with the 1000 W lamp. 478
- 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 Fig. 4. The temperature range measured was 23–38 °C.



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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 1000 W lamps on three different days. (b) Wavelength dependence of the temperature correction, derived from linear fits.

It can be seen from Figure 4 that the temperature correction factor for Brewer #150 shows no 490 491 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 492 in previous studies (Fountoulakis et al., 2017; Garane et al., 2006; Weatherhead et al., 2001). 493 Regarding the wavelength dependency, Garane et al. (2006) also obtained a correction factor 494 with no spectral dependency. However, other studies have found a polynomial dependency for 495 double monochromator Brewers (Fountoulakis et al., 2017; Lakkala et al., 2008). As already 496 mentioned, the temperature dependence is characteristic of each Brewer and could be responsible 497 for these differences. 498

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

502 **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 Fig. 5. To characterise the cosine error, the BAT (Brewer Angular Tester) device and a 150 W Xe arc lamp with an optic fibre 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).



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Figure 5: Cosine error characterization of Brewer #150. (a) Angular response measured for NS and WE 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.

520 Calculating this correction accurately is a hard task since it requires modelling the direct-to-521 global ratio, for each scan measured, using simultaneous ancillary measurements of aerosol 522 content, ozone, and surface albedo. Therefore, it is usual to perform the simulation with typical 523 or mean values of these atmospheric parameters (e.g. Fountoulakis et al., 2020; Cordero et al., 524 2008a). In this study, the influence of these assumptions will be analysed. Consequently, in Eq. (9) the cosine correction used is the one obtained with the mean values of ozone (287.5 DU) and

526 aerosols (1.371 and 0.039 alpha and beta Ångström exponents, respectively) of the study period

and is shown in Fig. 5. On the other hand, the cosine correction was also calculated by modelling
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: (1) the angular variability. A maximum error of 1° was estimated and (2) 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 $\pm 1^{\circ}$.

535 **4 Monte-Carlo simulated uncertainty**

To analyse the combined standard uncertainty of Brewer #150 UV measurements, the standard deviations $u_{\rm M}$ were evaluated considering the irradiance model, uncertainty sources, and values reported in Sect. 3. The data used correspond to 599 UV spectra measured under cloud-free conditions. The average Brewer #150 irradiance combined standard uncertainties for the wavelength range 290–363 nm as estimated by means of the Monte Carlo methodology are shown in Fig. 6.

- The combined standard uncertainty shows a marked spectral dependency, growing considerably with wavelength. Thus, its mean value ranges from 0.005 mW m⁻² nm⁻¹ at 290 nm to 7.5 mW m⁻² 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 (Fig. 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 (Fig. 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.



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Figure 6: Combined standard uncertainty of Brewer #150 UV irradiance spectra. (a) Mean, range of values and 5th and 95th percentiles of the 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°.

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





Fig. 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 (4 orders of magnitude), it may seem that the uncertainty is
negligible at short wavelengths. However, if the same spectrum is represented in logarithmic
scale (Fig. 7b) it becomes visible that the combined standard uncertainty is large, exceeding
100 % for wavelengths below 295 nm.

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In addition to the absolute values of the combined standard uncertainty, the analysis of its 574 relative values is of great interest due to the large variation of UV irradiance with wavelength. 575 Thus, Fig. 8 illustrates the relative values of the UV irradiance combined standard uncertainty, 576 $u_{\rm M}$ / E_2 , with respect to the wavelength. For wavelengths below 300 nm, the average relative 577 uncertainties exceed 100 %. This mean value was expected since the irradiance comes close to 578 579 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. 580 581 Furthermore, some spikes can be observed at specific wavelengths such as 302, 304.5 or 306.5 nm (Fig. 8a). They are caused by wavelength misalignment and have been already 582 reported in other Monte Carlo simulations (Cordero et al., 2008a; Schinke et al., 2020). Although 583 they result in high uncertainties at the mentioned specific wavelengths, their effect on the 584 585 average uncertainty is limited.

Regarding the variability, the 290–300 nm region shows the largest variability, of about 300 %. 586 This extreme high value is mainly produced by wavelength shift as well as PMT and thermal 587 noise. These uncertainty sources have a greater effect for very low signals, which are recorded at 588 589 short wavelengths and large SZAs. Their effect could be reduced by checking the wavelength 590 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 591 result the variability, defined as the difference between the 5th and the 95th percentiles, levels 592 off at around 1.3 %. This angular dependency agrees with the values reported by Bernhard and 593 594 Seckmeyer (1999).



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Figure 8: Relative combined standard uncertainty of the Brewer #150 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°.

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 Fig. 3). In this way, the dominant sources become visible.



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Figure 9: Contributions to the combined relative uncertainty of Brewer #150 UV irradiance measured on 10 September at a solar angle of (a) 65° and (b) 32°. Curve A depicts the combined relative uncertainty. Curve 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 consideringthe uncertainty sources of the outdoors measurements.

Figure 9 shows the results of such calculation. The influence of the radiometric calibration is 611 important for wavelengths larger than 305 nm. For this wavelength range (305 - 363 nm), the 612 mean relative uncertainty (curve A) is 3.6 % while the uncertainties arising from the radiometric 613 calibration (curve B) and the outdoors measurements (curve C) are 3.4 % and 0.5 % respectively. 614 615 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 616 dependence on SZA, the relative combined standard uncertainty shows no significant angular 617 dependence in this wavelength range. On the other hand, for wavelengths below 300 nm, the 618 619 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 620 from the outdoors measurements have a considerable angular dependence, the relative combined 621 standard uncertainty shows the same dependence. 622

The spectral expanded uncertainty $U_{\rm M}$ 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 measurements varies between 10 % at 300 nm and 7 % at 363 nm. Since the histogram of the spectral irradiance, as shown in Fig. 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 (QQ) plot.



Figure 10: Histogram of the simulated irradiance at a solar zenith angle of 32° resulting from 10^{5} iterations. (a) Global UV irradiance at 300 nm and (b) Global UV irradiance at 360 nm. The

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expected values and standard deviations are (a) $4.67 \text{ mW m}^{-2} \text{ nm}^{-1}$ and $0.18 \text{ mW m}^{-2} \text{ nm}^{-1}$; (b) 722.50 mW m⁻² nm⁻¹ and 25.69 mW m⁻² nm⁻¹.

Finally, the relative combined standard uncertainty of Brewer #150 can be compared with the 634 one obtained in previous studies. Garane et al. (2006) used a MKIII Brewer and conducted an 635 uncertainty analysis by applying the law of propagation of uncertainties (LPU). Their study 636 reports a 1σ uncertainty of approximately 5 % for the 290–363 nm range. This value is similar to 637 638 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 639 described in other publications (Bernhard & Seckmeyer, 1999; Gröbner et al., 2005). On the 640 other hand, the expanded uncertainty of Brewer #150 can also be compared to the values 641 642 reported in other studies for double monochromator spectroradiometers. Fountoulakis et al. (2020) used a Bentham DTM300 double monochromator and reported an expanded uncertainty 643 at 300 nm of the order of 10–12 % for SZAs lower than 75°. Gröbner et al. (2005) conducted an 644 uncertainty analysis for the QASUME and found an expanded uncertainty of 6.2 % for the 310-645 400 nm range and SZAs lower than 50°. Therefore, Brewer #150 average expanded and relative 646 combined standard uncertainty is comparable to those of other commercial double 647 monochromators. 648

649 **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 characterised 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.

659 Brewer #150 irradiance combined standard uncertainty depends significantly on wavelength and 660 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 661 region, it is mostly of the order of 3-4%. In this wavelength range, the uncertainty is 662 independent of solar zenith angle. In fact, the variability due to SZA is of the order of ~ 1 %. The 663 reason is that at this wavelength region the uncertainties arising from the radiometric calibration, 664 in particular the stability, have the biggest impact. Since these uncertainty sources have no 665 significant angular dependence, the relative uncertainty also shows no SZA dependency. 666 However, for wavelengths below 310 nm, the relative combined standard uncertainty does 667 668 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 669 shift. 670

The expanded uncertainty varies from 10 % at 300 nm to 7 % at 363 nm. Consequently, the UV dataset 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 erythemal 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 characterised and included in the uncertainty evaluation.

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690 **Open Research**

691 The ozone data used for the Brewer cosine correction in the study are available at https://eubrewnet.aemet.es/eubrewnet; The software SHICrivm used for the obtention of wavelength 692 shift is available at https://www.rivm.nl/en/uv-ozone-layer-and-climate/shicrivm/download; The 693 aerosol data used for the Brewer cosine correction are available at https://aeronet.gsfc.nasa.gov/cgi-694 bin/data_display_aod_v3?site=EI_Arenosillo&nachal=2&level=1; The dataset used for 695 the uncertainty evaluation is available at Zenodo via https://doi.org/10.5281/zenodo.8046474. The 696 697 software used for the implementation of the Monte Carlo technique is available at Zenodo via https://doi.org/10.5281/zenodo.8046562 with license Creative Commons 698 Attribution 4.0 699 International: The figures in this manuscript are prepared using MATLAB software (URL: 700 https://es.mathworks.com/products/matlab.html).

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