Response to Anonymous Reviewer #1

Authors' response to Reviewer #1 comments on "Evaluation of the uncertainty of the spectral UV irradiance measured by double- and single-monochromator Brewer spectroradiometers". The authors thank the Reviewer for the careful and constructive examination of the manuscript and reply to all comments below.

The answer is structured as follows: (1) comments from Reviewer #1, (2) authors' response and (3) authors' change in the manuscript.

(1) General comments

The paper presents a methodology to evaluate uncertainties in spectral UV irradiance measurements by Brewer spectroradiometers. The methodology considers most of the possible sources of uncertainty and has been applied on several instruments. In this respect, the study is innovative and useful for the uncertainty evaluation of the global Brewer network. However, it is alarming that the evaluation for one spectrum takes so long (8 hours), making the method impractical for evaluating large numbers of spectra.

The presentation is generally clear, but there are several places where clarifications are needed. See specific comments below.

(2) It took 8 hours to process both the spectrum and its sensitivity analysis. However, the time taken could be reduced by using a computer with a better performance and by optimizing the code. The latter can be achieved by using parallel programming or by using genetic algorithms such as particle swarm optimization.

(3) The previous information has been added to the text as follows: "Although this execution time could be reduced by optimising the code or using a computer with better performance, the MCM can be impractical to evaluate the uncertainty of Brewers long UV records."

(1) The language can certainly be improved. There are many typographical, syntax and grammar errors that can easily be corrected by careful reading. In my Technical Comments section below I have listed a few, but there are many more.

(2, 3) The manuscript has been carefully proofread to correct any typographical or grammatical errors.

(1) Therefore, my recommendation is that the paper would be suitable for publication in ACP, after addressing by comments below.

(1) Specific comments:

(1) 27: The difference between single and double monochromators is mainly due to stray light and not due to dark signal. I suggest deleting "and dark count".

(2, 3) The term "dark count" has been deleted and the phrase has been corrected to "the differences between single- and double-monochromator Brewers increase, due to stray light".

(1) 29-30: How the "irradiance of the calibration lamp" is involved in the uncertainty? I think you mean the uncertainty associated with the reference lamp calibration, therefore I suggest replacing "irradiance" with "uncertainty". The same applies to lines 418 and 618.

(2) It is the uncertainty of the irradiance emitted by the reference lamp. As the reviewer states, it is related to the calibration of the reference lamp.

(3) For greater clarity, the term "irradiance of the reference lamp" has been replaced with "uncertainty of the reference lamp" throughout the text.

(1) 153-155: I am not sure what you mean here: First you say that some uncertainties are considered in the analysis and then that you prefer to ignore them. Please clarify.

(2) Lines 153-155 refer to those uncertainty sources that have been included in the study, but their characterisation is not as thorough as the ones performed by other authors. For instance, the Brewer noise was determined by studying the signal-to-noise-ratio (SNR) from lamp measurements, as Bernhard and Seckmeyer (1999) or Cordero et al. (2012) did for the uncertainty evaluation of their instruments. In the RBCC-E campaign, Brewers were calibrated by performing 4 lamp scans. Therefore, the SNR was derived from a limited number of UV scans. However, we believe that, rather than ignoring these uncertainty sources, it is preferable to include them in the study, even if their characterisation is limited.

(3) To clarify this issue, the indicated lines have been rewritten as "In this study, the uncertainty sources have been characterised following the methodologies of Bernhard and Seckmeyer (1999), González et al. (2023, 2024), and Savastiouk et al. (2023). It should be noted that some of the uncertainties determined in this study (such as those related to noise, stray light, or radiometric stability) have their own uncertainty, as the data used for their estimation does not allow for appropriate statistics. Nevertheless, in all these cases, uncertainty values have been given and included in the Monte Carlo simulation".

(1) 157: Replace "counts" with "signal". It is better to use "signal" when you are referring generally to what is measured. This applies, for example, also to lines 159 and 160 and elsewhere.

(2, 3) Following the reviewer's suggestion, the term "counts" have been replaced with "signal" in lines 157, 159, and 160. To ensure consistency throughout the manuscript, the term "signal" has replaced "counts" whenever the text was referring generally to what is measured.

(1) 157: What do you mean by unprocessed? To what does this differ from (1)? My understanding after reading the next sections is that this category refers to uncertainties related to absolute irradiance, specifically to wavelength shifts, angular response and temperature dependence. All three affect the absolute irradiance rather than the raw (or unprocessed) irradiance.

(2) It is referring to the uncorrected UV irradiance. Even if the measured signal is processed, the derived irradiance is affected by other uncertainty sources (wavelength shifts, angular response, and temperature dependence) and needs correction.

(3) To clarify this issue, the term "raw irradiance" has been replaced with "uncorrected absolute irradiance" throughout the manuscript.

(1) 202: Does "40" refers to all dark signal measurements (which I think is too low) or to measurements at each temperature? Please specify.

(2) The 40 measurements mentioned in the text were the dark signal measurements performed only during the UV days (11–14 September). However, for the uncertainty estimation, all dark signal measurements performed during the campaign (from 5 to 15 September) were considered. This results in more than 100 dark signal measurements for all Brewers studied. Some Brewers

could perform less dark signal measurements than others due to calibration and necessary maintenance.

(3) The phrase has been corrected to "The number of available measurements depended on the instrument, but, in total, more than 100 dark signal measurements were recorded by each Brewer during the intercomparison campaign".

(1) 242, 245, 477: To which period do these drifts refer?

(2) The term "drift" was used to describe the uncertainty of the radiometric stability. It was determined by calculating the standard deviation from consecutive calibrations, as recommended by Bernhard and Seckmeyer (1999). To do so, all available calibration records from every Brewer were used. Unfortunately, not all Brewers studied had enough calibration files as they had undergone several modifications or were not calibrated frequently enough. Only two Brewers had enough calibration records to derive a standard deviation: Brewers #150 and #185. For Brewer #150, the yearly calibration files from 2005 to 2023 were used. On the other hand, to derive the uncertainty of Brewer #185, the monthly calibration records from 2021 to 2024 were used. No data from prior years have been considered as the instruments had different entrance optics.

(3) To avoid confusion, the term "drift" has been replaced with "uncertainty". Furthermore, the following information has been added: "For Brewer #150, the radiometric uncertainty was derived using the yearly calibration files from 2005 to 2023, while for Brewer #185 the uncertainty was calculated using the monthly calibration files recorded from 2021 to 2024. As mentioned earlier, no data from prior years could be used as the entrance optics of Brewers #150 and #185 were replaced in 2005 and 2021, respectively".

(1) 251: Since the spectral range is defined from short to long wavelengths, the irradiance is increasing rather than declining. You could cope with it more easily by saying "marked variability".

(2, 3) The previous information has been replaced by the term "marked variability".

(1) 269: It appears that not all uncertainties were considered for all instruments. You might consider summarizing in a table the types of uncertainties considered in each instrument.

(2, 3) Following the reviewer's suggestion, the following table has been added at the beginning of Section 3.1:

Table 2. Summary of the uncertainty sources considered for each Brewer under study. Red squares (–) represent the uncertainty sources not included in the evaluation, while green squares (×) indicate those uncertainty sources considered.

Uncertainty sources considered	Brewer ID									
	#117	#150	#151	#158	#172	#185	#186	#202	#228	#256
Noise	×	×	×	×	×	×	×	×	×	×
Dark signal	×	×	×	×	×	×	×	×	×	×
Stray light	×	–	×	–	–	–	–	–	–	–
Dead time	×	×	×	×	×	×	×	×	×	×
Distance adjustment	×	×	×	×	×	×	×	×	×	×
Uncertainty of the reference lamp	×	×	×	×	×	×	×	×	×	×
Radiometric stability	×	×	×	×	×	×	×	×	×	×
Wavelength shift	×	×	×	×	×	×	×	×	×	×
Temperature correction	–	×	–	–	–	–	–	–	–	–
Cosine correction	–	×	–	×	–	×	×	–	–	×

(1) 333-335: Why were spectra corrected for shifts only if they were measured at SZAs<90°?

(2) At larger SZAs, the surface UV irradiance decreases considerably and, as a result, the signal recorded by the instrument is close to its detection threshold. Furthermore, since the “El Arenosillo” Observatory is at sea level, the instability of the atmosphere increases for these larger values of the SZA due to sea turbulence. Therefore, including the UV scans measured at large SZAs would result in unreliable uncertainty estimations.

(3) The previous information has been added to the text as follows: “Larger SZA values have not been considered as the UV irradiance recorded in these conditions is small, close to the detection threshold of the Brewer spectrometers. Furthermore, since the “El Arenosillo” Observatory is at sea level, at large SZAs the instability of the atmosphere increases due to sea turbulence.

(1) I think the second sentence complicates the discussion. You can simply say: "Only spectra recorded at SZA's smaller than 90° were used in this study."

(2, 3) The second sentence has been deleted and replaced with “Only spectra recorded at SZAs smaller than 90° were used in this study”.

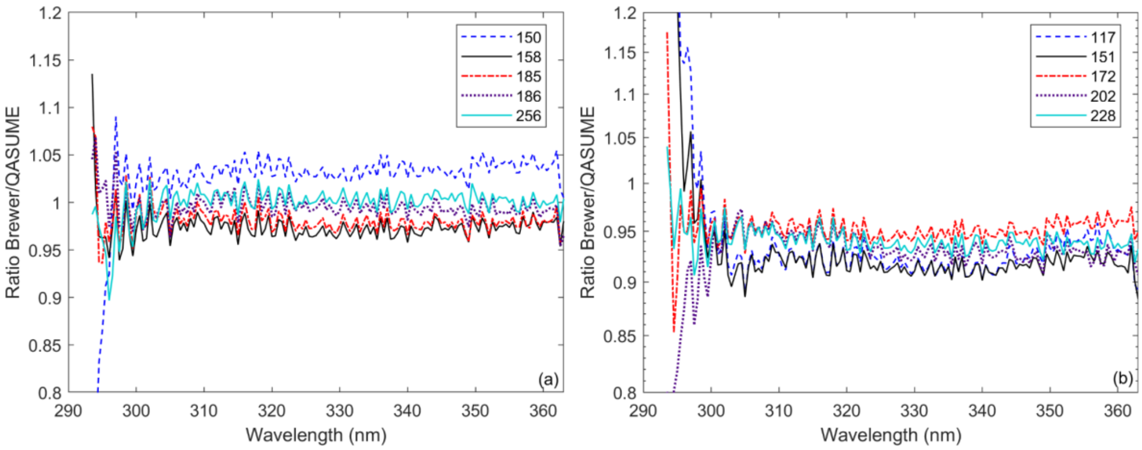
(1) 359: What about cloudy conditions? Other sources of uncertainty are also involved. Maybe you could discuss briefly what happens under cloudy conditions.

(2) Under cloudy conditions, the methodology for calculating the cosine correction and noise of the spectroradiometer changes. The cosine correction depends on the SZA, the AOD, and the cloudiness. Therefore, cloud cover must be an input introduced in libRadtran when calculating the direct-to-global ratio. On the other hand, noise was derived from stable measurements recorded using a reference lamp. However, clouds have a strong effect on surface UV irradiance and can lead to short-time fluctuations. Under these circumstances, noise needs to be thoroughly characterised by using, for example, a group of near outdoors measurements. Nevertheless, this is difficult for a Brewer spectroradiometer since it takes approximately 5 minutes to record a complete UV spectrum.

(3) The previous information has been added to the text as follows: “Under cloudy conditions, the methodology used for calculating the cosine correction and noise must be adapted. As the cosine correction depends on the cloudiness, the cloud cover must be considered when modelling the direct-to-global ratio. Furthermore, clouds strongly affect the surface UV irradiance and can lead to short-time variations. As a result, noise needs to be thoroughly characterised. For example, by studying groups of near outdoors measurements. For Brewer spectroradiometers, this can be difficult as the instrument does not have enough temporal resolution to detect fast fluctuations of solar UV irradiance”.

(1) 371: Good agreement cannot be assessed by this figure. If ratios were shown against one instrument (e.g., the QASUME or the average / median of all instruments) the level of agreement would have been more evident.

(2) Indeed, the agreement between instruments should be assessed using a reference instrument. The following figure has been obtained by studying the ratio from each Brewer to the QASUME reference (2023-09-13 at 14:00 UTC):



It can be seen that the agreement between the instruments is within ±10 % from unity for wavelengths above 310 nm. Nevertheless, the analysis of the instruments’ performance (QA) is beyond the scope of this study (QC).

(3) The phrase “Furthermore, there is good agreement between all the Brewers between 310 and 360 nm” has been deleted from the manuscript.

(1) 378: I am not sure if Figure 2 is necessary. It is expected that the standard uncertainty will increase with wavelength and solar elevation since the irradiance increases. In contrast Figure 3 is more meaningful to discuss.

(2, 3) Following the reviewer’s comment, Figure 2 has been deleted from the manuscript and the phrases “As an example, Fig. 2 shows the absolute combined standard uncertainties of the UV irradiances measured on 13 September 2023 at 14:00 UTC (40° SZA). The scale presented is logarithmic to highlight the differences between the Brewers at short wavelengths” have also been removed.

(1) 393: Better say, at the end of the sentence: "... and some Brewers showed almost no SZA dependency, as shown later in Figure 4".

(2, 3) Following the reviewer's suggestion, the phrase has been corrected to "For most Brewers, the relative uncertainty values ranged from 2.5 % to 4 % for wavelengths between 300 and 360 nm and some Brewers showed almost no SZA dependency, as shown later in Figure 4".

(1) 406: In fact, half of the 10 Brewers considered show some SZA dependency and half are not; so, I wouldn't say "most Brewers".

(2, 3) The phrase has been corrected to "Figure 4 shows that the relative combined standard uncertainty of half of the Brewers has no angular dependency". This affirmation has also been corrected in the Conclusions section.

(1) 416: In this section, a table summarizing the ranges of uncertainties due to different factors together with the combined uncertainty would be useful.

(2, 3) The following information has been added to the sensitivity analysis section:

"As a summary, Table 3 shows the relative individual and combined standard uncertainties for each Brewer under study at SZAs below 80° and wavelengths larger than 300 nm. Larger SZAs and shorter wavelengths have not been included in this table as the relative uncertainties increase greatly since the UV irradiance measured approaches zero (see Fig. 1).

Table 3. Range of the uncertainties produced by each uncertainty source individually and the combined standard uncertainty for SZAs below 80° and wavelengths larger than 302 nm for each of the Brewers studied.

ID	Individual uncertainty (%)										Combined uncertainty (%)
	Noise	Dark signal	Stray Light	Dead time	Dist. Adjust.	Unc. Lamp	Stab.	λ shift	Temp. Corr.	Cos. Corr.	
#117	0.070–5.3	0.060–21	≤2.1	≤0.17	0.23	1.2–1.3	3.0	0.004–1.6	–	–	3.2–22
#150	0.029–3.1	0.0045–2.3	–	≤0.84	0.24	0.61–0.75	3.6	0.004–0.82	0.0091–0.037	0.43–0.51	2.9–5.1
#151	0.080–2.9	0.043–20	≤1.1	≤0.58	0.23	0.43–0.61	3.0	0.014–3.8	–	–	3.1–20
#158	0.048–2.6	0.0013–2.1	–	≤0.66	0.28	0.85–1.4	3.0	0.014–2.4	–	0.80–1.6	3.3–5.5
#172	0.026–1.3	0.012–6.9	–	≤0.44	0.23	0.39–0.67	3.0	0.015–1.2	–	–	3.0–7.8
#185	0.073–2.8	0.0034–6.4	–	≤0.28	0.23	0.60–1.1	2.8	0.003–0.63	–	0.84–1.6	2.4–7.7
#186	0.039–2.0	0.010–2.6	–	≤0.85	0.23	1.2–1.3	3.0	0.005–1.2	–	1.6–3.3	3.6–5.8
#202	0.19–6.7	0.0022–2.9	–	≤1.5	0.23	0.60–1.1	3.0	0.01–1.3	–	–	3.1–8.0
#228	0.042–2.8	5.7e-4 – 0.94	–	≤0.20	0.23	0.60–1.1	3.0	0.004–1.1	–	–	3.1–4.4
#256	0.048–2.8	6.6e-4 – 1.3	–	≤0.60	0.23	0.60–1.1	3.0	0.005–0.68	–	0.92–1.8	3.2–4.8

In the following, the influence of each uncertainty source on the total uncertainty budget will be described in greater detail.”

(1) 417-418: The relative contribution to the combined uncertainty is based (or at least it is shown in Figure 5) by the two example spectra. I think it would be more representative to show average contributions from a larger number of spectra recorded for several days in a narrow range of SZAs.

(2, 3) Following the reviewer’s comment, Figures 5 and 6 have been updated to show the average contributions of the uncertainty sources over a narrow range of SZAs. This has resulted in the following figures and captions:

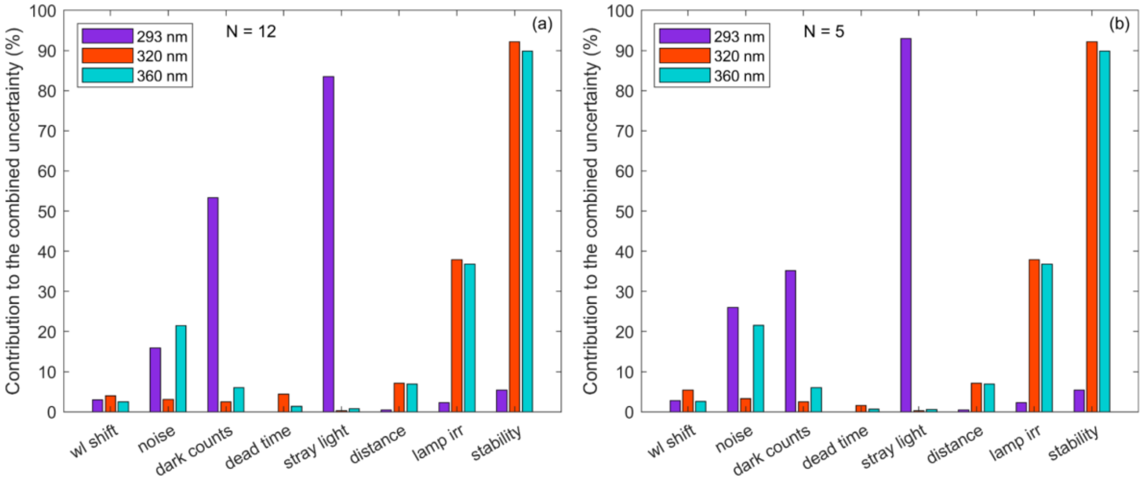


Figure 5. Relative contribution of the uncertainty sources of a single monochromator Brewer (#117) to the combined standard uncertainty of the UV spectrum measured at three wavelengths (293. 320, and 360 nm) and two SZAs, (a) 33° and (b) 63°. Each contribution was calculated from the average over a ±1° SZA band.

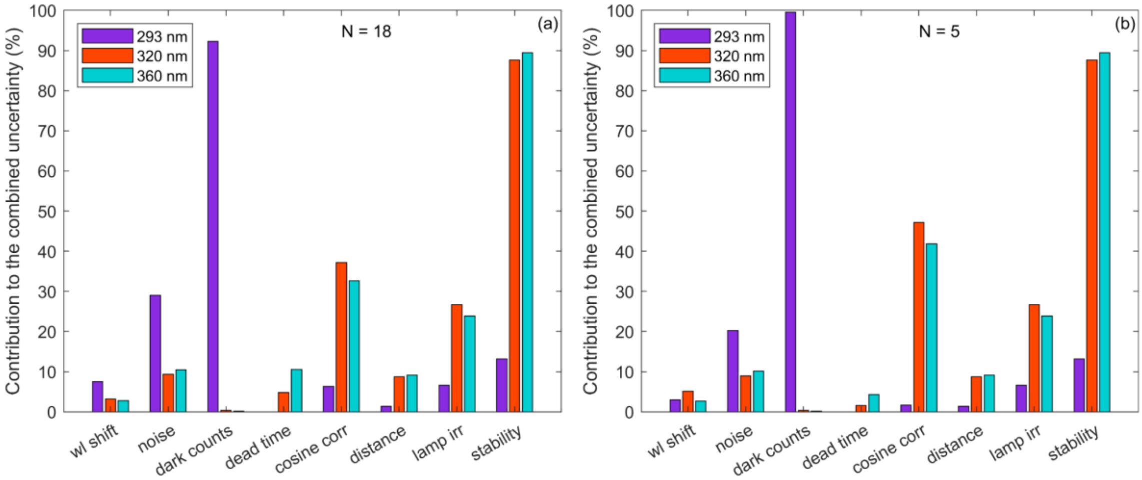


Figure 6. Relative contribution of the uncertainty sources of a double monochromator Brewer (#185) to the combined standard uncertainty of the UV spectrum measured at three wavelengths (293. 320, and 360 nm) and two SZAs, (a) 33° and (b) 63°. Each contribution was calculated from the average over a ±1° SZA band.

(1) 424: You might consider including a table with individual and total uncertainties for each of the Brewers considered.

(2) A table with the individual and the combined standard uncertainties has been added to the sensitivity analysis section, as asked earlier in Line 416.

(1) 452: How do your results on Dead Time compare with those derived by Fountoulakis et al., 2016? https://amt.copernicus.org/articles/9/1799/2016/

(2, 3) Following the reviewer's comment, the following information has been added to Section 4.2.4: "Finally, the dead time contribution can be compared to the one reported by Fontoulakis et al. (2016). Their study shows that if the DT ranges from 15 to 45 s and has an error of 2 ns, it leads to irradiance uncertainties of 0.12–0.13, 0.25–0.28, and 0.69–1.13 % for signals of 1, 2, and 5 million counts s^{-1}, respectively. These values are similar to the ones found for all Brewers, except Brewer #202, which has an uncertainty larger than 2 ns. For these Brewers, the irradiance uncertainty is less than 0.15, 0.35, and 0.9 % for signals of 1, 2, and 5 million counts s^{-1}, respectively".

(1) 506: Caption of Fig. 7: This figure shows the relative standard uncertainty (not the combined). Please correct the axis title and caption.

(2, 3) The axis title and caption of Figure 7 have been corrected so they include the term "relative standard uncertainty" instead of "combined standard uncertainty".

(1) 517-525: Although the contents of this paragraph are correct, they are not very relevant to the topic of the paper. The authors have already published a work on the TCO uncertainties using the same methodology.

(2, 3) The mentioned paragraph and the references therein have been removed from the manuscript.

(1) 556-562: I am afraid that the uncertainty in quantifying the effects of UV radiation on materials is much higher than the uncertainty in UV measurements.

(2, 3) Following the reviewer's comment, the following phrase has been added at the end of the indicated paragraph "Nevertheless, it should be noted that the uncertainty in quantifying the effect of UV radiation on materials can be much higher than the uncertainty in UV measurements itself".

(1) 581-586: Note that photolysis frequencies are estimated from actinic flux measurements which are not measured by Brewer spectroradiometers. However, generally speaking, the estimation of uncertainties of relevant instruments can benefit from this study.

(2, 3) The following information has been added at the end of the indicated paragraph "Although ozone photolysis rates cannot be derived from Brewer spectroradiometers measurements, the methodology used in this study is general and could be of use to other instruments that do measure actinic flux".

(1) 591: In the conclusions section, I suggest discussing the uncertainties against those reported in previous studies. Does this study show significantly different results from the uncertainties in spectral UV irradiance usually quoted in the literature?

(2, 3) Following the referee's suggestion, the uncertainty determined for both single and double Brewers have been compared with those reported in previous studies. The following discussion has been added to the manuscript: “The relative combined standard uncertainties of the Brewers used in this study can be compared with the ones obtained in previous studies. Garane et al. (2006) determined a combined standard uncertainty of 5.3 % at 320 nm for a single Brewer (MKII version). This value is slightly larger than the one obtained in our work at 320 nm (3.1–3.3 %). This is likely produced by cosine correction. While Garane et al. (2006) included this uncertainty source in their evaluation, none of the single Brewers participating in the RBCC-E campaign had their cosine error characterised. Regarding the double Brewers studied, their UV irradiance uncertainty ranges between 2.5 and 5 % for wavelengths larger than 300 nm. These values are similar to the uncertainty found by Garane et al. (2006). They reported a relative uncertainty of 4.8 % for their double Brewer. Furthermore, the uncertainty of the double Brewers studied is also comparable to the European reference units, QASUME I and QASUME II. Hülsen et al. (2016) found relative uncertainties of 3.85 % and 3.67 % at 300 nm for QASUME and QASUME II, respectively. Moreover, the irradiance uncertainties determined in our work are similar to the ones described in other publications (Bernhard & Seckmeyer, 1999; Fountoulakis et al., 2020). Therefore, the relative combined standard uncertainties determined in this study are comparable to those of other UV spectroradiometers”.

(1) 623: Apart from the need to monitor the wavelength shifts, it is essential to reduce them through accurate determination of the instrument’s wavelength scale and frequent wavelength calibrations.

(2, 3) The paragraph has been corrected and the following information has been added: “(d) monitor wavelength shifts and reduce them below 0.05 nm through frequent wavelength calibrations and accurate determination of the instrument wavelength scale”.

(1) Technical comments:

(1) 30: Rephrase to "measured UV irradiance decreases, the dark signal"

(2, 3) The phrase has been changed to “As the measured UV irradiance decreases, the dark signal, stray light, and noise become dominant”.

(1) 99: Replace "using" with "by"

(2, 3) The term “using” has been replaced with “by”.

(1) 177: Please rephrase to: "These values are deemed reliable as they were derived by analyzing data from over 20 single Brewers."

(2, 3) The phrase has been modified according to the referee’s suggestions.

(1) 191: replace "was" with "is"

(2, 3) The term “was” has been replaced with “is”.

(1) 289: Insert “by” before “integrating”

(2, 3) The term “by” has been inserted as indicated.

(1) 294: Replace “diffuser error” with “diffuse error”

(2, 3) The typo has been corrected.

(1) 295: “derived for inhomogeneous sky radiance distribution”

(2, 3) The phrase has been corrected to “derived for inhomogeneous sky radiance distribution”.

377: Replace “displaying” with “display”

(2, 3) The term “displaying” has been replaced with “in a similar way than”, for greater clarity.

(1) 445: Delete “those of”

(2, 3) The term “those of” has been deleted.

456: Replace “as SZAs decrease” with “at small SZAs”

(2, 3) The term “as SZAs decrease” has been replaced with “at small SZAs”.

(1) 603: Replace “depended on the wavelength and SZA, increasing as wavelength rose and SZA declined.” with “increases with increasing wavelength and decreasing SZA”.

(2, 3) The phrase has been corrected following the referee’s suggestion.

(1) 604: Replace “tripled” with “are triple”

(2, 3) The term “tripled” has been replaced with “are three times higher than”, for greater clarity.

(1) 624: Replace "committed in” with “associated with”

(2, 3) The term “committed in” has been replaced by “associated with”.