

## Second response letter to Referee #2 on the manuscript “Monte Carlo method for determining uncertainty of total ozone derived from direct solar irradiance spectra: Application to Izaña results”

Authors: Anna Vaskuri, Petri Kärhä, Luca Egli, Julian Gröbner, and Erkki Ikonen

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**Authors:** We thank Anonymous Referee #2 for the valuable comments that helped us in improving the manuscript. We have included below our detailed responses to the remaining comments. Our response to the comments regarding the introduction and the specific comments 1 and 2 can be found in our first response letter addressed to Referee #2.

### COMMENTS

“the only characteristics of the instruments described in the manuscript are their spectral range. I believe that a study of the instrumental uncertainties should provide a thorough description of the instruments”

**Authors:** To provide more information on the campaign and better description of the instruments, we rename Section 2 as “ATMOZ field measurement campaign and instrument description”. The following paragraphs after line 10 on page 3 now describe the instruments used:

“The data sets measured by three different spectroradiometers were studied in this work. These spectroradiometers use different techniques to measure the spectral distribution of radiation. Monochromator-based spectroradiometers like QASUME, measure one nearly monochromatic wavelength band at a time, and thus measuring the full spectrum is relatively slow. On the other hand, they usually have significantly better stray light properties than array-based spectroradiometers like BTS and AVODOR, which image the full spectrum at once by dispersing the incoming radiation towards a photodiode array.

QASUME spectroradiometer collects and guides the incoming radiation with input optics and a quartz fiber bundle to the entrance slit of a Bentham DM150 double monochromator (Gröbner *et al.* (2005)). One wavelength at a time is selected by rotating the two gratings of the double-monochromator. Then, the monochromatic signal is measured with a photomultiplier tube. QASUME is usually operated in global spectral irradiance mode (Gröbner *et al.* (2005); Hülsen *et al.* (2016)), but during the campaign it was equipped with a collimator tube with a full opening angle of 2.5° allowing the measurement of direct solar spectral irradiance (Gröbner *et al.* (2017)). The measurement range of QASUME during the campaign was limited to 250 nm – 500 nm with a step interval of 0.25 nm, so that one spectrum was measured every 15 minutes. To ensure stable outdoor measurements, the double-monochromator of QASUME was mounted inside a temperature-controlled weather-proofed box (Hülsen *et al.* (2016)).

BTS spectroradiometer utilizes a stationary grating and a back-thinned cooled CCD array detector, mounted in a Czerny-Turner configuration (Zuber *et al.* (2017a, b)). To measure direct solar spectrum, BTS was equipped with a collimator tube with a full opening angle of 2.8° designed by PTB, and it uses an internal filter wheel system with 8 filter positions together with a specific measurement routine to reduce stray light. BTS was mounted on a solar tracker, EKO STR-32G by EKO Instruments Co., Ltd., with pointing accuracy better than 0.01°. A weather-proof housing with temperature control allows BTS operation at the ambient temperatures from –25 °C to 50 °C. During the ATMOZ campaign, the housing temperature of BTS was measured to be stable within 0.1 °C (Zuber *et al.* (2017b)). The measurement range of BTS was 200 nm – 430 nm with a step size of 0.2 nm during the campaign. One spectrum was measured every 45 seconds.

AVODOR spectroradiometer has a stationary grating and a back-thinned cooled CCD array detector in a Czerny-Turner configuration. AVODOR measures the spectrum from 200 nm to 540 nm with a step size of 0.14 nm in the UV region. During the ATMOZ campaign, the field of view of AVODOR was limited to 1.5° by a commercial collimator tube used, J1004-SMA by CMS Ing.Dr.Schreder GmbH. The spectral range of AVODOR was limited between 295 nm and 345 nm by a combination of two solar blind filters to reduce stray light from the visible and infrared parts of the solar spectrum. The solar blind filters were mounted between the collimator tube and the fiber entrance of the spectroradiometer. One spectrum was measured every 30 seconds.”

“a Monte carlo model was employed, but important details such as the number of samples that were used, the obtained statistical distribution, etc. are not mentioned;”

**Authors:** We add new sentences after line 9 on page 10:

“Each standard uncertainty of TOC in Fig. 4 was estimated from the MC results obtained by running the TOC retrieval 1000 times so that the phases  $\phi_i$  and the weights  $\gamma_i$  of the base functions were independent at each round. Retrieved TOC deviations resemble Gaussian distribution when the order of complexity of the deviation function is  $N \geq 2$ .”

“the uncertainty components written in the tables are not properly motivated in Sect. 5. Each number should be accompanied by a clear explanation;”

**Authors:** We amend the text describing Tables 1, 2, and 3 to describe all components included. The tables will be located in chapter 4 in the new manuscript:

“The uncertainties due to radiometric calibration include factors such as the uncertainty of the standard lamp used, and the additional uncertainty due to noise and alignment. QASUME has been validated using various methods, thus the uncertainty due to calibration is low (Hülsen *et al.* (2016)). For QASUME and BTS, we assume the correlations to be equally distributed between *full* correlation, *unfavourable* correlation, and *random* correlation (Kärhä *et al.* (2018)). Spectra measured with AVODOR are significantly noisier, thus half of the uncertainty is associated to the *random* component. Values for instability of the calibration lamp are based on long-term monitoring. The lamp irradiances have been noted to gradually drop with no significant wavelength structure within the wavelength region concerned. Non-linearity values are estimations of the operators of the devices. Non-linearity is typically manifested so that the responsivity of the device changes gradually from high readings to low readings. This can cause significant change in the TOC values, thus we assume the correlation type to be

*unfavourable*. Uncertainties due to device stability and temperature dependence are based on long-term monitoring. The changes have been found to be independent on wavelength in the region concerned, thus *full* correlation is assumed. Noise is the average standard deviation of typical measurements at noon over the wavelength region concerned. The wavelength scales of the devices have been checked using emission lines of gas discharge lamps. The uncertainty values given are the estimated standard deviations of the possible remaining errors after corrections. Wavelength error can introduce a significant change in TOC, because it introduces an error in the form of the derivative of the spectral irradiance. Thus, *unfavourable* correlation is assumed. Most of the uncertainty components are slightly wavelength dependent but to simplify simulations, average uncertainty values are used over the wavelength range between 300 nm and 340 nm.”

“the discussion about the deviation of the three instruments is very superficial (e.g., "... the reason a the systematic deviation either in the linearity, stray light properties, or the calibration of the device") and inconclusive. How is it connected to the main topic of the paper?”

**Authors:** Thanks to the improved atmospheric model and the improved TOC results, we can remove that sentence. Please, see the first response letter addressed to Referee #2 for full details.

“language inaccuracies are listed in the "Technical corrections" section. One for all: "Izaña results" in the title is very generic. At the Izaña atmospheric observatory (not simply "Izaña"), several activities are organised and the title should appropriately tell which campaign was taken into consideration;”

**Authors:** We change the title of our AMT Discussion manuscript as “Monte Carlo method for determining uncertainty of total ozone derived from direct solar irradiance spectra: The results of ATMOZ field measurement campaign at the Izaña Atmospheric Observatory”.

“there is a persistent interchange of terms that should not be mixed: uncertainty, deviation, error, etc. (e.g., "uncertainty induced by deviation", p. 10 line 9);”

**Authors:** In our opinion, we have used those terms correctly, except for “error function” that we change to “deviation function” so that it cannot be confused with “Gauss error function” that is often called simply “error function” or “erf”.

Uncertainty is an estimate of the possible error that there may be in a quantity. Spectral errors may further contain systematic deviations. In our analysis we go through systematic deviations (errors) that the uncertainties of the input quantities permit. The variances of TOC obtained with the deviated spectra then give uncertainties for the output quantity TOC. Description of the analysis requires using terms:

- **Standard uncertainty** is the square root of the variance of a probability distribution.
- **Expanded uncertainty** specifies the value of the measurand with 95% confidence. For a Gaussian probability distribution, expanded uncertainty is twice the standard uncertainty ( $k = 2$ ).
- **Error** is a discrepancy between the measured value and the “true” value.
- Due to the nature of Monte Carlo method, in each Monte Carlo round, we introduce an arbitrary **spectral deviation** in the input parameter and observe how it changes TOC value. When we run Monte Carlo TOC retrieval multiple times, we can calculate the standard uncertainty from the variation in the output TOC.

“QASUME is not only a "high-quality reference instrument ... at PMOD/WRC": it is the World reference UV spectroradiometer! Anyway, it should be explained how a global irradiance instrument could measure direct solar irradiance spectra (p. 2 line 5: how was the field of view "limited"?);”

**Authors:** We revise the sentence on page 2, line 1 as:

“One of the instruments is QASUME (Gröbner *et al.* (2005)) that is the World reference UV spectroradiometer at the World Radiation Center (PMOD/WRC).”

We also include a new paragraph about QASUME in Section 2:

“QASUME spectroradiometer collects and guides the incoming radiation with input optics and a quartz fiber bundle to the entrance slit of a Bentham DM150 double monochromator (Gröbner *et al.* (2005)). One wavelength at a time is selected by rotating the two gratings of the double-monochromator. Then, the monochromatic signal is measured with a photomultiplier tube (PMT). QASUME is usually operated in global spectral irradiance mode (Gröbner *et al.* (2005); Hülsen *et al.* (2016)), but during the campaign it was equipped with a collimator tube with a full opening angle of 2.5° allowing the measurement of direct solar spectral irradiance (Gröbner *et al.* (2017)). The measurement range of QASUME during the campaign was limited to 250 nm – 500 nm with a step interval of 0.25 nm, so that one spectrum was measured every 15 minutes. To ensure stable outdoor measurements, the double-monochromator of QASUME was mounted inside a temperature-controlled weather-proofed box (Hülsen *et al.* (2016)).”

## TECHNICAL CORRECTIONS

“p. 1 line 2, "directional irradiance": do you mean "direct irradiance"?”

**Authors:** Yes, we revise the sentence as: “We demonstrate a Monte Carlo model to estimate the uncertainties of total ozone column (TOC), derived from ground-based direct solar spectral irradiance measurements.”

“p. 1 line 2, "correlations in the spectral irradiance data" is too generic: do you mean correlation of data within the same spectrum and measured at different wavelengths?”

**Authors:** We agree that the sentence is too generic. We revise the sentence as: “The model estimates the effect of possible systematic spectral deviations in the solar irradiance spectra on the uncertainties in TOC retrieved.”

“p. 1 line 20, "analyse uncertainties": uncertainty of what? I guess in ozone retrievals...;”

**Authors:** Corrected according to reviewer’s suggestion. We revise the sentence as: “... data and analyse uncertainties in ozone retrievals for three different spectroradiometers used ...”

“p. 2 line 1-2: is the order in which the instruments are described (QASUME, AVODOR and BTS) the same as in the abstract (high-end scanning spectroradiometer, high-end array spectroradiometer and roughly adopted instrument)? If not, please avoid confusing the reader;”

**Authors:** We revise the last paragraph in the introduction as:

“In this paper, we introduce a new method for dealing with possible correlations in spectral irradiance data and analyse uncertainties in ozone retrievals for three different

spectroradiometers used in a recent intercomparison campaign at Izaña, Tenerife, to demonstrate how it can be used in practice. One of the instruments is QASUME (Gröbner *et al.* (2005)) that is the World reference UV spectroradiometer at the World Radiation Center (PMOD/WRC). The second one is an array-based high-quality spectroradiometer BTS2048-UV-S-WP (BTS) from Gigahertz-Optik (Zuber *et al.* (2017a, b)), operated by PTB. The third one is an array-based spectroradiometer AvaSpec-ULS2048LTEC (AVODOR) from Avantes, operated by PMOD/WRC. The field of view of the spectroradiometers has been limited so that they measure direct spectral irradiance of the Sun, excluding most of the indirect radiation from the remainder of the sky.”

“p. 2 line 11: "total ozone content" is mentioned since the beginning of the paper, but formally defined only in page 6 (Eq. 4). Can you move Eq. 4 a bit earlier?”

**Authors:** This is true, and thus we move Eq. (4) of our AMT Discussion manuscript to Section 2 so that now it is the first equation of the manuscript.

“p. 3 line 1, "vertical profiles were not implemented": what do you mean?”

**Authors:** We mean that we did not split the atmosphere to horizontal layers at different altitudes and then perform the ozone retrieval fitting. Instead, we use effective atmospheric layers with effective altitudes and temperatures. We revise the sentences in AMT Discussion manuscript as:

“Our ozone retrieval method uses one atmospheric layer to reduce computational complexity. With the one-layer model, the ozone absorption cross-section is a function of the effective temperature, and the relative air mass is a function of the effective altitude of the ozone layer.”

“p. 3 line 2, "shift the absolute values": values of what? "but should not have an effect": can you justify this hypothesis?”

**Authors:** PMOD/WRC has a version of the code where the atmosphere is split to horizontal layers at different altitudes and piece-wise calculation of the light transmission is performed. Estimation on possible differences in the TOC uncertainty produced by different layer models will be removed.

“p. 3 line 10, "the uncertainties ...are standard deviations": standard deviation of what series/samples? Can you mention which kind of measurements were employed?”

**Authors:** We revise the sentence as: “The uncertainties stated for  $h_{\text{eff}} = 26 \text{ km} \pm 0.5 \text{ km}$  and  $T_{\text{eff}} = 228 \text{ K} \pm 1 \text{ K}$  are standard deviations estimated from the vertical profiles in Fig. 1, measured during the campaign on the days 7, 14, 21 Sept. 2016.”

“p. 3 line 11, "One of the instruments was the QASUME...": already said;”

**Authors:** We remove this sentence as it was already mentioned.

“p. 3 line 14, "every 15 minutes": explain that use of a scanning radiometer involves slower measurements, and why;”

**Authors:** We include a new paragraph in Section 2:

“The data sets measured by three different spectroradiometers were studied in this work. These spectroradiometers use different techniques to measure the spectral distribution of radiation. Monochromator-based spectroradiometers like QASUME, measure one nearly monochromatic wavelength band at a time, and thus measuring the full spectrum is relatively slow. On the other hand, they usually have significantly better stray light properties than array-based spectroradiometers like BTS and AVODOR, which image the full spectrum at once by dispersing the incoming radiation towards a photodiode array.”

We also give measurement intervals of BTS and AVODOR.

“**p. 3 line 15:** what is the spectral range of AVODOR? It is legitimate to say that an instrument "has been corrected"?”

**Authors:** Regarding the former comment, we revise the text in Section 2 as:

“AVODOR spectroradiometer has a stationary grating and a back-thinned cooled CCD array detector in a Czerny-Turner configuration. AVODOR measures the spectrum from 200 nm to 540 nm with a step size of 0.14 nm in the UV region. During the ATMOZ campaign, the field of view of AVODOR was limited to 1.5° by a commercial collimator tube used, J1004-SMA by CMS Ing.Dr.Schreder GmbH. The spectral range of AVODOR was limited between 295 nm and 345 nm by a combination of two solar blind filters to reduce stray light from the visible and infrared parts of the solar spectrum. The solar blind filters were mounted between the collimator tube and the fiber entrance of the spectroradiometer. One spectrum was measured every 30 seconds.”

Regarding the latter comment, we revise the sentence as:

“To measure direct solar spectrum, BTS was equipped with a collimator tube with a full opening angle of 2.8° designed by PTB, and it uses an internal filter wheel system with 8 filter positions together with a specific measurement routine to reduce stray light.”

“**p. 4 Table 1:** is this table useful? The same numbers are repeated in Table 4. Also, provide bibliographic references about how each term in the "Standard uncertainty" column was calculated;”

**Authors:** We move Tables 1, 2, and 3 in the AMT Discussion manuscript to Section 4. We keep Table 1 although some of its data are repeated in Table 4, as its last row states the combined  $k = 1$  uncertainty of the spectral measurement. It also makes the describing text clearer when all spectroradiometers are described in similar tables.

We also provide description how standard uncertainties in Tables 1 – 3 are obtained:

“The uncertainties due to radiometric calibration include factors such as the uncertainty of the standard lamp used, and the additional uncertainty due to noise and alignment. QASUME has been validated using various methods, thus the uncertainty due to calibration is low (Hülsen *et al.* (2016)). For QASUME and BTS, we assume the correlations to be equally distributed between *full correlation*, *unfavourable correlation*, and *random correlation* (Kärhä *et al.* (2018)). Spectra measured with AVODOR are significantly noisier, thus half of the uncertainty is associated to the *random* component. Values for instability of the calibration lamp are based on long-term monitoring. The lamp irradiances have been noted to gradually drop with no significant wavelength dependent structure within the wavelength region concerned. Non-

linearity values are estimations of the operators of the devices. Non-linearity is typically manifested so that the responsivity of the device changes gradually from high readings to low readings. This can cause significant change in the TOC values, thus we assume the correlation type to be *unfavourable*. Uncertainties due to device stability and temperature dependence are based on long-term monitoring. The changes have been found to be independent on wavelength in the region concerned, thus *full* correlation is assumed. Noise is the average standard deviation of typical measurements at noon over the wavelength region concerned. The wavelength scales of the devices have been checked using emission lines of gas discharge lamps. The uncertainty values given are the estimated standard deviations of the possible remaining errors after corrections. Wavelength error can introduce a significant change in TOC, because it introduces an error in the form of the derivative of the spectral irradiance. Thus, *unfavourable* correlation is assumed. Most of the uncertainty components are slightly wavelength dependent but to simplify simulations, average uncertainty values are used over the wavelength range between 300 nm and 340 nm.”

Regarding the paragraph above, one reference was updated in the AMT Discussion manuscript:

Kärhä P., Vaskuri A., Pulli T., and Ikonen E.: Key comparison CCPR-K1.a as an interlaboratory comparison of correlated color temperature, *J. Phys.: Conf. Ser.*, 972, 012012, 2018. doi:10.1088/1742-6596/972/1/012012

To clarify the uncertainty components in Table 4, we also include new sentences in the AMT Discussion manuscript before line 5 on page 14:

“For components (a) – (d) in Table 4, the mechanism of contributing to the uncertainty of TOC is known. We know the standard uncertainty of the O<sub>3</sub> layer altitude of 26 km to be  $u = 0.5$  km, so we vary the altitude accordingly and note the variance of the resulting TOC.”

“**p. 5 line 2**, "fitting the ozone retrieval": can a single quantity be fitted?”

**Authors:** We revise the sentence as: “They are needed when fitting the spectra at the Earth surface modelled with the ozone retrieval to the measured spectra.”

“**p. 5 line 5**, "affects uncertainties with a factor of sqrt(N)": do you mean 1/sqrt(N)? If so, why the Brewer - which measures the irradiance for the ozone retrieval at only 4 wavelengths - is considered a reference in the paper?”

**Authors:** We revise the sentence as: “In our full spectrum TOC retrieval, the number of data points  $N$  which is smaller with a larger wavelength step interval, affects uncertainties with a factor of  $1/\sqrt{N}$  (Kärhä *et al.* (2017b); Poikonen *et al.* (2009)).”

We include a new reference in the AMT Discussion manuscript:

Poikonen T., Kärhä P., Manninen P., Manoocheri F., and Ikonen E.: Uncertainty analysis of photometer quality factor  $f'_1$ , *Metrologia*, 46, 75–80, 2009.

Regarding the latter question, our full spectrum retrieval method does “averaging” in the wavelength domain, whereas Brewer spectrophotometer does it in the time domain. Brewer can measure up to tens of seconds to get millions of photons, so that the photon noise reduces to a level of 0.1%. At this low noise level, it is not critical that only four wavelengths

are used. Averaging over multiple measurement sequences, regardless of the retrieval method used, reduces the noise in TOC by a factor of  $1/\sqrt{N_r}$ , where  $N_r$  is the number of repetitions.

“p. 6 line 1-2: give credit to Bouguer, Lambert and Beer (not Huber et al. 1995);”

**Authors:** We include references to Bouguer, Lambert, and Beer. We also have to acknowledge Huber *et al.*, as the complete ozone retrieval using spectral irradiance measurements and least-squares fitting method have been documented in that paper, and it is also one of the most useful references of our manuscript. Thus, we revised the beginning of Section 3 as:

“In this study, we use an atmospheric ozone retrieval algorithm in many aspects similar to the article by Huber *et al.* (1995). The relationship between the spectral irradiance  $E_s(\lambda)$  at the Earth surface and the extra-terrestrial solar spectrum  $E_{\text{ext}}(\lambda)$  is based on Beer-Lambert-Bouguer absorption law (Beer (1852); Lambert (1760); Bouguer (1729)) as ...”

New references are included in the AMT Discussion manuscript:

Beer A.: Bestimmung der Absorption des rothen Lichts in farbigen Flüssigkeiten, *Annalen der Physik und Chemie.*, 86, 78–88, 1852.

Bouguer P.: *Essai d’optique sur la gradation de la lumière* (Paris, France: Claude Jombert, 1729) pp. 16–22.

Lambert J. H.: *Photometria sive de mensura et gradibus luminis, colorum et umbrae* (Augsburg ("Augusta Vindelicorum"), Germany: Eberhardt Klett, 1760).

“p. 6 Eq. 3: a reference to the used extraterrestrial spectrum (QASUME-FTS) should be mentioned just after the equation;”

**Authors:** Corrected according to reviewer’s suggestion. We include a new sentence in our AMT Discussion manuscript after line 6 on page 6:

“The QASUME-FTS data set by Gröbner *et al.* (2017) was used as the extra-terrestrial spectrum  $E_{\text{ext}}(\lambda)$ .”

“p. 6 line 12: theta is the angle at the observing site, not the angle between vacuum-to air interface;”

**Authors:** Yes, it is the angle at the observing site. Fortunately, this was a mistake only in the manuscript. It was correctly used in the code. First, effect of the solar zenith angle  $\theta_v$  at the vacuum-to-air interface at the effective altitude  $h_{\text{eff}}$  on the relative air mass  $m$  is defined as

$$m = \frac{1}{\cos(\theta_v)}. \quad (1R)$$

After taking the Earth curvature into account, we obtain the relative air mass dependence on the solar zenith angle  $\theta$  at the observing site as

$$m = \frac{1}{\cos\left[\arcsin\left(\frac{R}{R+h_{\text{eff}}}\sin\theta\right)\right]}, \quad (2R)$$

where  $R$  is the Earth radius.

“p. 7 line 10: the extinction coefficient is defined as  $d\tau/dz$ , thus it has nothing to do with beta;”

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**Authors:** Corrected according to reviewer's suggestion. Now, we call  $\beta$  as the Ångström turbidity coefficient.

**"p. 7 line 11:** avoid the expression "terrestrial spectrum", the radiation is from the sun, not from the Earth. Use "solar spectrum at the Earth surface";"

**Authors:** Corrected according to reviewer's suggestion.

**"p. 7 line 22,** "As can be seen, the signal-to-noise ratios ... differ": how can I see it from the figure, without any explanation?"

**Authors:** It is true that the baseline noise was not clearly shown in Fig. 3 in our AMT Discussion manuscript due to the scaling of the axes. We replace Fig. 3 with Fig. 1R below and revise the paragraph referring to this figure. The new paragraph reads:

"Figure 3 presents examples of measurements and modelled values for the spectroradiometers used in this work. As can be seen, the signal-to-noise ratios of the devices differ significantly among different spectroradiometers. All spectra measured by QASUME spectroradiometer are excellent above  $10^{-6} \text{ Wm}^{-2}\text{nm}^{-1}$  with the dynamic range of approximately four orders of magnitude. The dynamic range for BTS is approximately two orders of magnitude and for AVODOR it is less than two orders of magnitude. Based on the analysis in Appendix A, we use absolute least squares minimisation in TOC estimation with  $w(\lambda) = 1$  for BTS and AVODOR as it is not affected by the lowest irradiance levels where the stray light and noise are dominant. For QASUME, we use the relative least squares minimisation with  $w(\lambda) = E(\lambda)^{-2}$  as it has been used in the past for monochromator-based spectroradiometers, e.g. by Huber *et al.* (1995). The shortest modelling wavelength for the spectroradiometers in this work was set to 300 nm since the typical stray light corrections are not effective below 300 nm (Nevas *et al.* (2014)). The upper wavelength limit was set to 340 nm with all three spectroradiometers as the ozone absorption is not effective above that wavelength."

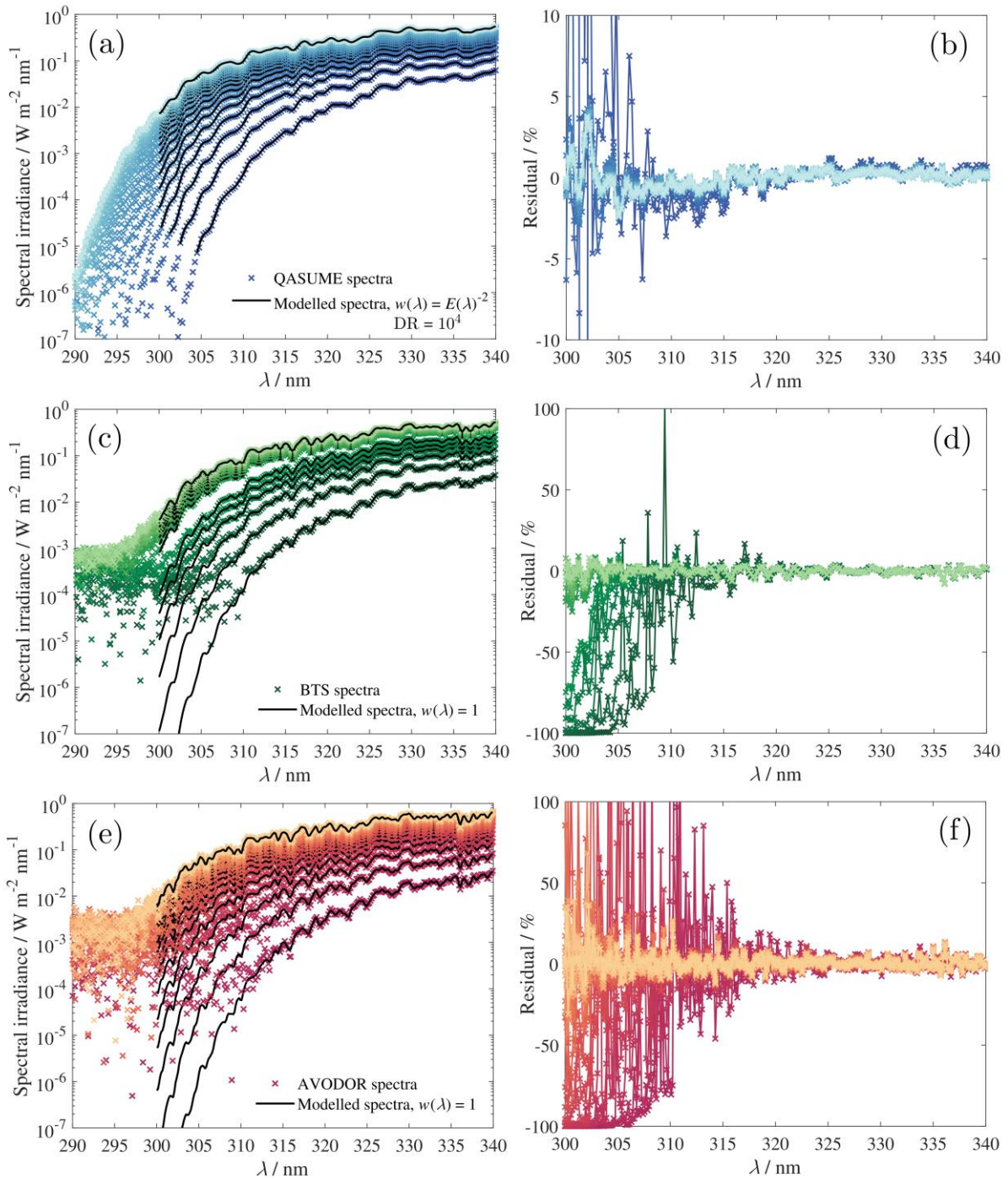


Figure 1R. Examples of fitting the atmospheric model to the direct ground-based solar UV spectra between 300 nm and 340 nm for QASUME (a–b), BTS (c–d) and AVODOR (e–f). In figures on the left hand side, the coloured symbols indicate measured spectra, and the black solid curves indicate modelled spectra. Figures on the right hand side show the relative spectral residuals of the fits. In (a), the abbreviation DR refers to the dynamic range of QASUME data used in the least squares fitting.

“p. 9 line 3: “noise” usually defines a random variable, while stray light is a systematic effect. Don’t put them together in the same sentence;”

**Authors:** The new data analysis using absolute least squares fitting for AVODOR and BTS makes this sentence obsolete. The whole paragraph will be rewritten.

“p. 10, Eq. 11: define "u";”

**Authors:** We include a following text after line 5 on page 10: “... where  $u(\lambda)$  is the relative standard uncertainty of the spectrum.”

“p. 10 line 20, "does not have any internal limitation to the shape of the error function": what do you mean?”

**Authors:** The MC uncertainty model does not assume any particular spectral shape of the deviation. Fourier series has a property that in its full form it can produce any shape of deviation. This takes place at the Nyquist criterion, where  $N$  is equal to half the number of wavelengths available. Also with smaller values of  $N$ , the MC parameters can account for unknown spectral shapes of lower complexity.

“p. 11 line 3, "components stating fractions": what do you mean?”

**Authors:** We revise the sentence as: “The uncertainty components divided to the three correlation types have been analysed with the new model. The other components (a)–(d) have been solved using traditional MC modelling because the mechanism for the uncertainty propagating to TOC is known.”

“p. 12 Table 4: why is "X" used instead of "TOC"?”

**Authors:** We replace “ $\tau_X m_X$ ” with “in exponent” in Table 4 to avoid confusion.

“p. 12 line 2: was "r" defined?”

**Authors:** Yes, as there is a sentence before Eq. (12): “Division of the correlation to the three categories introduced are stated for each row as fractions  $r_{full}$ ,  $r_{unfav}$ , and  $r_{random}$ .”

“p. 13 line 20, "a wavelength shift will introduce unfavourable correlations": why? The ozone cross section has a complex shape;”

**Authors:** The ozone absorption cross-section has a complicated shape and the spectral deviation due to the wavelength shift is then also complicated. In other words, the uncertainty due to this complex correlation causes higher uncertainty than noise could cause. Thus, we assume *unfavourable* case of correlation.

“p. 13 lines 24-25, "the wavelength shift... should be corrected for the extraterrestrial spectrum": or vice-versa?”

**Authors:** We revised the sentence as “the wavelength shift ... should be corrected **from** the extra-terrestrial spectrum”.