A guide to measuring solar UV spectra using array spectroradiometers

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Guideline

[1] Version V 1.0 indicates the state of the art at the beginning of the EMPR project. The guideline will be adopted in further versions with new innovations from the project.

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[1] Version V 1.0 is the guideline at the beginning of the EMPR project. The guide will be adopted with new results from the project in a further version

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1. Introduction

This guide is intended to summarize the requirements when making routine measurements of global irradiance of solar UV radiation using array spectroradiometers. So far in many networks world-wide broadband or filter radiometers are used for routine measurements and in a few cases scanning spectroradiometers are operated. The latter have the great advantage to provide full information about the solar spectrum. Therefore one can apply any biological weighting function (action spectrum) to derive its dose rate, whereas this product can be derived from broadband or narrow band filter radiometers only with very limited accuracy. However, scanning spectroradiometers have the clear disadvantage that they are very expensive and need a sophisticated operator for maintenance. The recently developed array spectroradiometers offer now an opportunity to utilize the advantages of the scanning spectroradiometers and still have a reasonable price. Also very fast data acquisition is now possible and maintenance is less demanding because array spectroradiometers do not have moving parts and therefore they are quite robust. However, array spectroradiometers, due to the principle of their operation, are only single monochromators and therefore suffer significantly from stray light, biasing irradiance measurements typically in the UV-B wavelength range. This is a severe problem for measurements of solar UV radiation due to the sharp cut off of the solar UV spectrum as a consequence of ozone absorption. Therefore it is important to follow strict procedures when using array spectroradiometers for measuring spectral solar UV radiation in order to achieve the desired quality of the results.

Greater details about background information, instrument characterisation and general guidelines can be found in the GAW-report No. 191 “Instruments to measure solar ultraviolet radiation – Part 4: array spectroradiometers” [1]. Further detailed information about specific characteristics of array spectroradiometers (e.g. wavelength calibration or stray light correction algorithms) will be investigated within this project, and an update of this document will be carried out, when those will be available. Additional relevant information for best practice of solar measurements can be found in the GAW publications 125 [2], 126 [3] and 146 [4].

In the following chapters, suggestions are given for the selection and characterisation of array spectroradiometers prior to use for outdoor measurements, then for the measurement procedure itself and finally for post processing of the raw data to derive the final results.

2. Recommended specifications for array spectroradiometers

Adapted from [1], the recommended specifications for measurement of global irradiance are:

Table 1: *General recommendations for global irradiance measurements by array spectrometers as proposed by the GAW report No. 191 [1].*

Maximum irradiance at 400 nm	> 2 W m^{-2} nm^{-1}
Detection threshold	< 10^{-3} W m^{-2} nm^{-1}
Stray light	< 10^{-3} W m^{-2} nm^{-1}
Bandwidth (FWHM)	< 1 nm
Slit function	< 10^{-3} of maximum at 2.5 FWHM away from centre
Sampling wavelength Interval	< 0.2 FWHM (> 5 pixels/FWHM)
Wavelength precision	< ±0.05 nm
Wavelength accuracy	< ±0.1 nm
Nonlinearity	< 2 % for signals more than 50 times above detection threshold
Instrument temperature	Monitored and sufficiently stable to maintain overall instrument stability
Frequency of recording spectra	> 0.1 Hz
Overall calibration uncertainty	< ±10% (unless limited by detection threshold)
Scan date and time	Recorded with each spectrum such that timing is known to within 1 s
Cosine error (a) for incidence angles <60° (b) to integrated isotropic radiance (c) azimuth error	 < ±5 % < ±5 % < ±3 %
Levelling accuracy	< 0.2°

In addition to the remarks to these specifications given in [1], the following comments are relevant for the application of array spectroradiometers for routine observations, where the main aim is not the investigation of the spectral structure of the solar spectrum but the determination of weighted dose rates (weighted integrals over a broad spectral range). The uncertainties determined in the following calculations do not include any uncertainty components listed in table 1. The main purpose of this study is to illustrate the specifications which need to be reached in order to determine weighted dose rates from measured solar spectra. Thus, the wavelength range, as well as the corresponding dynamic range and minimum detection threshold are estimated which are required to obtain a weighted dose rate from the measured solar spectrum, starting at the calculated cut-on wavelength. A comprehensive uncertainty including the contributions from the uncertainty sources as listed in table 1 is beyond the scope of this document, and will be dealt with in a separate document. Specifically, the requirements for determining the dose rates for four commonly used action spectra (CIE Erythema [5], Vitamin D3 [6], Total UVB (280 – 315 nm), and DNA Damage [7]) are given in the next section:

2.1. Dynamic range

The required dynamic range covers 2 to 5 orders of magnitude, depending on the type of action spectrum, the atmospheric conditions (mainly solar zenith angle (SZA) and total column ozone (TO_3)) and the desired uncertainty contribution of the calculated dose rates. The dynamic range required to determine each of the four action spectra with an uncertainty of either 1% or 5% was determined from modelled solar spectra using the LibRadtran package [8], with the following parameters : 16 Streams, Standard atmosphere Midaltitude summer (afglms), Albedo 0.035, AOD: β= 0:01, α = 1.6, Altitude = 0 m.a.s.l., Pressure=1013.25 mbar, SSA=0.95, g=0.7, TO3 =200 to 500 DU, SZA = 0 to 85°.

Based on the desired uncertainty contribution for each weighted dose rate, all irradiances below the cut-on wavelength are set to zero and then integrated with the respective action spectrum. The results are presented in Appendix A (figures A1a – A8a) and summarized in table 2, where the required dynamic range is stated for the four action spectra in dependence on the desired uncertainty:

Table 2: *Required dynamic range to achieve an uncertainty contribution of 1%, respectively 5% for the following four weighted dose rates in dependence of SZA and TO_3. The minimum dynamic range is obtained for SZA=0° and TO_3=200 DU, while the maximum dynamic range is obtained at an SZA of 85° and TO_3 of 500 DU.*

	Dynamic range [order of magnitude] Min. / Max.							
Uncertainty	Erythema		Vitamin D3		UVB		DNA	
1%	2.8	3.7	2.4	4.4	2.1	4.0	3.5	5.1
5%	2.1	2.8	2.0	3.8	1.6	3.3	2.8	4.2

Practically, to cover the required five orders of magnitude, the analog-to-digital converter of the array spectrometer needs a resolution of 17 bit; to achieve 4 orders of magnitude, 14 bit are sufficient. If the resolution is lower, then this could be partly compensated by making a higher number of repetitions of the individual measurement and using the average.

2.2. Detection threshold (irradiance and wavelength)

The required order of magnitude (see table 2) implies a minimum wavelength and minimum absolute irradiance which has to be measured by the array spectrometer to achieve a specific uncertainty for the respective action spectra. The irradiance at the respective cut-on wavelength is presented in Appendix A (figures A1b/c – A8b/c) and summarized in table 3, assuming the atmospheric parameters listed previously.

Table 3: *Required irradiance detection (a) and wavelength (b) threshold (Min./Max.) to achieve an uncertainty contribution of 1%, respectively 5% for the following four weighted dose rates in dependence of SZA (0°-85°) and TO_3 (200 DU-500 DU). The highest (most tolerant) threshold is obtained for SZA=0° and TO_3=200 DU, while the lowest irradiance and wavelength threshold is obtained at an SZA of 85° and TO_3 of 500 DU.*

a)	**Detection threshold** [$mWm^{-2}nm^{-1}$] Min. / Max.			
Uncertainty	Erythema	Vitamin D3	UVB	DNA
1%	0.02 / 3.0	0.004 / 6.5	0.01 / 13.1	0.001 / 0.59
5%	0.13 / 11.7	0.014 / 20.3	0.044 / 49.2	0.006 / 2.7
b)	**Cut-on Wavelength** [nm] Min. / Max.			
Uncertainty	Erythema	Vitamin D3	UVB	DNA
1%	294.9 / 308.8	296.6 / 304.8	298.4 / 306.8	291.6 / 303.8
5%	297.3 / 315.9	299.4 / 307.1	302.1 / 309.4	294.8 / 306.8

2.3. Prescribed detection threshold

Contrary to state-of-the art scanning spectroradiometers using photomultiplier detectors, array spectroradiometers use silicon based solid state detectors with corresponding low sensitivities at short wavelengths in the UV. Therefore, the detection threshold is a critical parameter defining a particular array spectroradiometer. Detectable means that the average of repeated measurements (after subtraction of the dark measurements) is higher than the standard deviation of the dark measurements (Signal-Noise-Ratio; SNR ≥ 1, see [1]). As shown in table 3, detection thresholds much lower than 1 $mWm^{-2}nm^{-1}$ need to be achieved if weighted dose rates need to be determined under **all** atmospheric conditions.

A more practical approach might therefore be to specify the detection threshold, which can be realistically achieved by an array spectroradiometer (with reasonable uncertainty, SNR >> 1) as limiting criteria, and then to determine the corresponding uncertainty by calculating the weighted dose rate starting at the corresponding cut-on wavelength. The uncertainties in dependence of SZA and TO_3 are shown in Appendix B (figures B2-B5) for the four action spectra mentioned previously for a detection threshold of **1 $mWm^{-2}nm^{-1}$**. As can be seen in the figures of Appendix B, an uncertainty of 1% (respectively 5%) in the weighted dose rates can generally be achieved (for the clear sky atmospheric conditions mentioned earlier) at SZA smaller than about 50° (respectively 75°) for the CIE Erythema, Vitamin D3, and UVB action spectra, while the DNA weighted dose rates can be measured with uncertainties of less than 5% for SZA smaller than 50° and uncertainties of less than 10% for SZA smaller than 65°. The uncertainties rise sharply for increasing SZA, but do not depend significantly on the TO_3.

2.4. Stray Light

Stray light is the most stringent characteristic when using array spectroradiometers for measuring spectral solar UV irradiance. The recommended specifications cannot be reached with instruments available at the moment without further data processing by applying suitable correction algorithms. The recommended specification in table 1 has to be understood as the final result after post processing. Of course, the better the stray light suppression within the array-spectroradiometer is performed, the smaller the correction and thus the smaller the remaining uncertainty. Practically, the final data should not be affected by stray light for irradiance levels above 1 $mWm^{-2}nm^{-1}$. Below that threshold, the data could be affected by stray light and should pragmatically be set to 0, which corresponds to a cut-on wavelength between 293 nm and 316 nm, depending on SZA and TO_3 (see Appendix B, figure B1).

2.5. Bandwidth and sampling wavelength interval

Since for this guide the main application of using array spectroradiometers is the derivation of weighted dose rates by weighted integration of the spectrum over a broad wavelength range, the requirements for bandwidth and sampling wavelength interval can be less strict than stated in [1]. A bandwidth of < 2 nm and >2 pixels per FWHM are sufficient.

2.6. Instrument characterisation

The determination of the characteristics of the array-spectroradiometer has to be carried out before the instrument is set up for routine measurements. This holds especially for:

- Wavelength calibration (establishing the relation between pixel number and wavelength)
- Determination of the slit function (FWHM, shape)
- Determination of the stray light level for the whole spectral range
- Determination of the structure of the dark signal: for some instruments the dark signal has a specific structure in dependence on wavelength, which can be determined once with high accuracy and then be applied after the solar measurement during the post processing. This structure may also depend on the selected integration time and on the temperature of the instrument
- Determination of the linearity. This includes two components: at a fixed setting of the integration time the linearity has to be determined for the whole range of counts using radiometric methods, i.e. varying the irradiance level; the relation between counts at different integration times (relative to a standard integration time) may

deviate from the ratio of the integration times and this dependency may be different for different counts.

- Determination of the spectral responsivity (irradiance calibration). When a calibrated lamp is used for this determination it is important that also for this measurement the appropriate post processing is applied, especially the stray light correction algorithm.

2.7. Setup

After the characterisation of the array-spectroradiometer in the laboratory, some specific requirements for the setup for routine outdoor measurements have to be considered, in addition to the general consideration for measurements of solar radiation:

- For an array-spectroradiometer currently available it is absolutely necessary to operate them in a temperature-stabilized housing. The dark signal of these instruments (output signal when no radiation is entering the instrument) usually depends in a very sensitive way on the temperature of the instrument. Furthermore, also the calibration of the wavelength-setting, as well as the irradiance calibration depend on temperature, and usually the instruments increase their temperature during operation. These dependences are very complex and therefore it is generally not recommended to apply a temperature correction, but to stabilize the temperature of the instrument with a regulated system (e.g. by using Peltier-elements and a temperature controller unit). It was found that the level of stabilization has to be in the order of 0.1° to avoid negative effects of temperature changes.

- As the dark signal should be determined before each regular measurement, it is necessary to use a setup with an automated shutter, which will block the incoming radiation from entering the instrument. In most cases, the input optics (the diffuser for measuring global irradiance) is connected with a quartz fibre with the body of the instrument, and usually at the entrance port of the instrument a shutter can be installed, which is under control of the operating computer.

- The connection of the quartz fibre to the input optics on the one hand and to the instrument on the other hand has to be very reproducible, because even very small variation of this connection will have a significant effect on the responsivity of the array-spectroradiometer [9].

3. Measurement protocol

The best quality of measurements can be achieved if the available dynamic range of the instrument is completely used. This can be achieved by selecting the integration time in a way that overexposure of any pixel is avoided but the maximum number of output counts is close to the maximum (> 90%) of the analog-to-digital converter. Therefore the following sequence is suggested:

- Opening the shutter
- Making a test measurement with a short integration time (e.g. 5 milliseconds) to estimate how long the optimal integration time can be. For this calculation, of course, also the changing dark current with changing integration time has to be considered, but the accuracy of a default look-up table (for the specific stabilization temperature) of this dependency is accurate enough. Then the possible number of repetitions of the measurement is calculated, based on the predefined total measurement time (e.g. 1 sec or 5 sec). Alternatively, the number of repetitions could be predefined (e.g. 10). This has the advantage of a constant statistical quality of all recorded spectra, but in turn the total measurement time is changing with changing integration time and the measurement may overlap with the next measurement or be in conflict with a desired short measurement time to follow fast changes due to moving clouds.
- Setting the instrument to the calculated integration time
- Closing the shutter
- Making a dark measurement with the calculated number of repetitions and calculating the mean over all pixels
- Opening the shutter
- Making the real measurement with the calculated number of repetitions
- Determination of the detection threshold and uncertainty of absolute irradiance measurement (see [1]) for the calculated integration time and number of repetitions.
- Closing the shutter
- Saving the raw data (counts versus pixel number) together with a header, which has to include at least date and time of the start of the measurement, the integration time, the number of repetitions, the dark signal, the temperature, place of measurement and instrument identification

This measurement sequence will be repeated in a predefined period, e.g. every minute or every 5 minutes.

4. Post processing

After finishing a solar measurement, several steps are necessary to derive the final, calibrated spectral data from the raw data (saved in a measurement file together with the information in a header), which then can be further processed for applying any weighting function.

1. Subtraction of the dark signal (which can be a mean of repeated dark signal measurements) from the entire measured signal resulting in the solar-signal
   resulting data as [pixelnumber counts]

2. Correction of the solar-signal for nonlinearity
   resulting data as [pixelnumber counts]

3. Conversion to a standard integration time including its nonlinearity correction
   resulting data as [pixelnumber counts/s]

4. Subtraction of the structure of the dark signal
   resulting data as [pixelnumber counts/s]

5. Conversion of the pixel number to wavelength
   resulting data as [nm counts/s]

6. Conversion to a uniform wavelength grid by a linear interpolation of 2 neighbouring pixels (and not aggregation of the data)
   resulting data as [nm counts/s]

7. Stray light correction
   resulting data as [nm counts/s]

8. Division by the responsivity function
   resulting data as [nm $Wm^{-2}nm^{-1}$]

9. Spectral weighting with a desired weighting function (e.g. erythema action spectrum or Vitamin D formation spectrum) and integration over all wavelengths, where the measured solar spectrum is >0 and the weighting function is >0. Special attention is necessary that the measured solar spectrum is really set to 0 for the short UV wavelengths where the measurement after stray light correction is dominated only by the noise level. Otherwise, the weighting and integration procedure could lead to significant errors.

Specific comments:

- When determining the spectral structure of the dark signal, the steps 1) – 3) are necessary.
- When a measurement of the reference lamp is carried out for the determination of the irradiance calibration, steps 1) – 7) are necessary. Then the spectral responsivity is calculated by dividing the [counts/s] by the irradiance of the reference lamp (as stated in the calibration certificate. The result for the responsivity is given as [nm (count/s)/($Wm^{-2}nm^{-1}$)]

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Appendix A

Introduction

The objective of this sensitivity analysis is to investigate the impact of the uncertainty of solar UV irradiance measurements from array spectrometers on the following (most common) action spectra such as, CIE Erythema, Vitamin D3, Total UVB and DNA damage.

The main question is: <u>What is the required dynamic range in solar UV irradiance measurements to obtain an estimation of the weighted irradiance of less than 1% or 5%?</u>

Dataset

The study was performed using model spectra obtained with the "LibRadtran" radiative transfer package[1]using as main variables the solar zenith angle (SZA) and the total column ozone (TO_3). The spectra were computed over the range 280 to 450 nm for the SZA range 0 to 85° and TO_3 from 200 to 500 nm. A total of 288 (=18 SZA x 16 TO_3) spectra were calculated.

Procedure

i) From the maximum irradiance (max_{irr}) of a specific spectrum the value is divided by the predefined order of magnitude (= $10^{m\text{-}order}$) assuming that the array-spectrometer is able to accurately measure the irradiance from the maximum intensity to the minimum intensity (min_{irr}). The ratio of the maximum intensity and the chosen order of magnitude is defined as following:

$$min_{irr} = max_{irr} / 10^{m\text{-}order} \qquad \text{(Eq. 1)}$$

ii) Irradiances below the critical minimum irradiance (min_{irr}) and shorter than the wavelength *wl-cut* at min_{irr} were set to 0, assuming that measurements below this cut-off were not reliable.

iii) The spectra of both, the original data (obtained by the model) and the modified spectra as described in ii) - iii) were weighted with the action spectra for Erythema , Vitamin D3, UVB and DNA.

iv) From these weighted spectra the integral of irradiance between 280 and 450 nm was calculated for all SZA and TO_3. To estimate the fractional bias of the weighted spectra for all possible combinations of SZA and TO_3, the ratio

[1] Mayer, B. and Kylling, A.: Technical note: The libRadtran software package for radiative transfer calculations - description and examples of use, Atmos. Chem. Phys., 5, 1855-1877, doi:10.5194/acp-5-1855-2005, 2005

between the original model data and the modified spectra was calculated as defined in following:

$$Fractional\ Deviation = \frac{TRUE}{\substack{Uncertain \\ Measurement}} = \frac{\int_{280nm}^{450\ nm} E(\lambda, SZA, O3) * C(\lambda) d\lambda}{\int_{wl-cut}^{450\ nm} E(\lambda, SZA, O3) * C(\lambda) d\lambda} \qquad \text{(Eq.2)}$$

Where $E(\lambda, SZA, O3)$ is a specific solar UV spectrum, $C(\lambda)$ denotes the normalized weighting function for the different action spectra (a-d) and *wl-cut* indicates the cut-off wavelength defined in ii).

v) Finally, the order of magnitude, where the maximum of the fractional deviation (equation 2) is less than 0.01 for all SZA and $T0_3$ combinations was obtained. The longest wavelength (*wl-cut*) at which the irradiance was set to 0 was also determined for all SZA and TO_3.

Results

The results for the required order of magnitude (subfigures a), the minimal cut-off wavelength (subfigures b) and minimal cut-off global irradiance absolute intensity (subfigures c) are presented for uncertainty of 1% (Figure A1-A4) and uncertainty of 5% (Figure A5-A8) for all 4 action spectra.

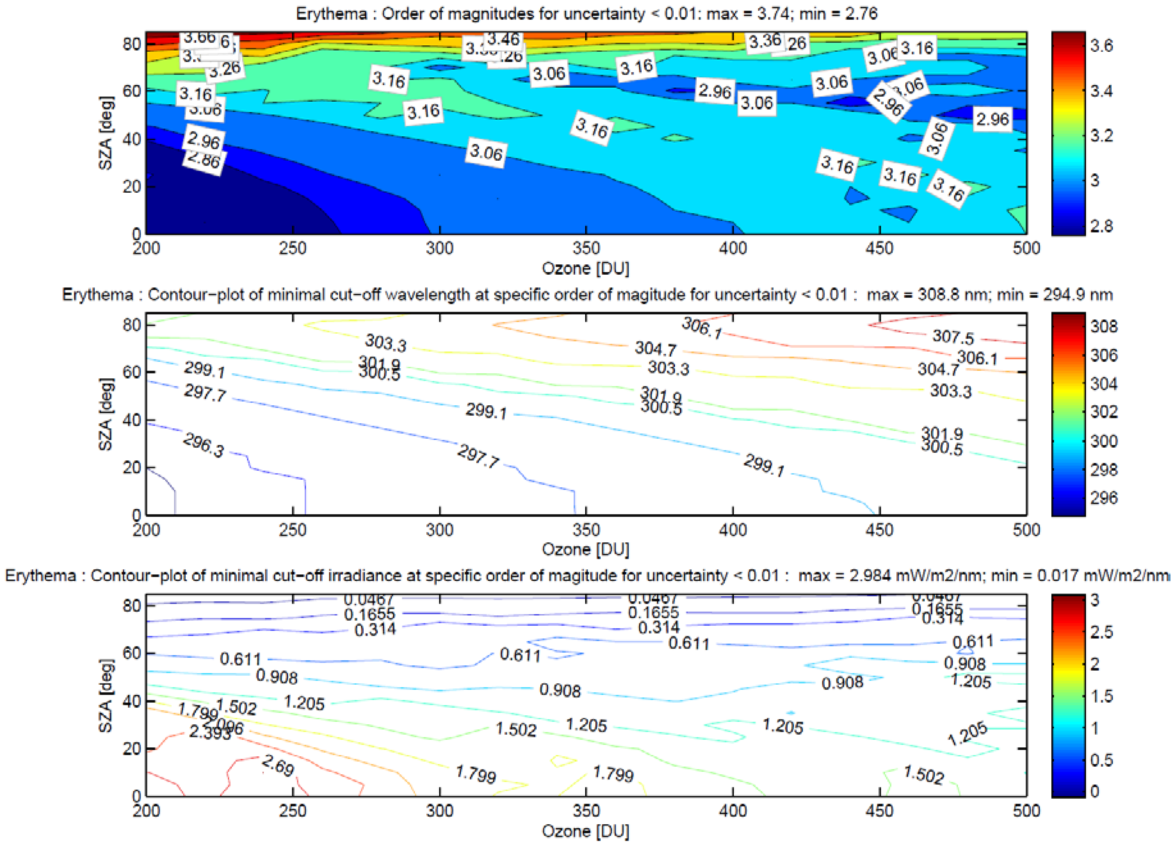

Figure A1: Erythema weighted dose rate for uncertainty < 1%: a) orders of magnitude (upper panel), b) minimal wavelength (middle panel) and c) minimal detection threshold of absolute irradiance (lower panel).

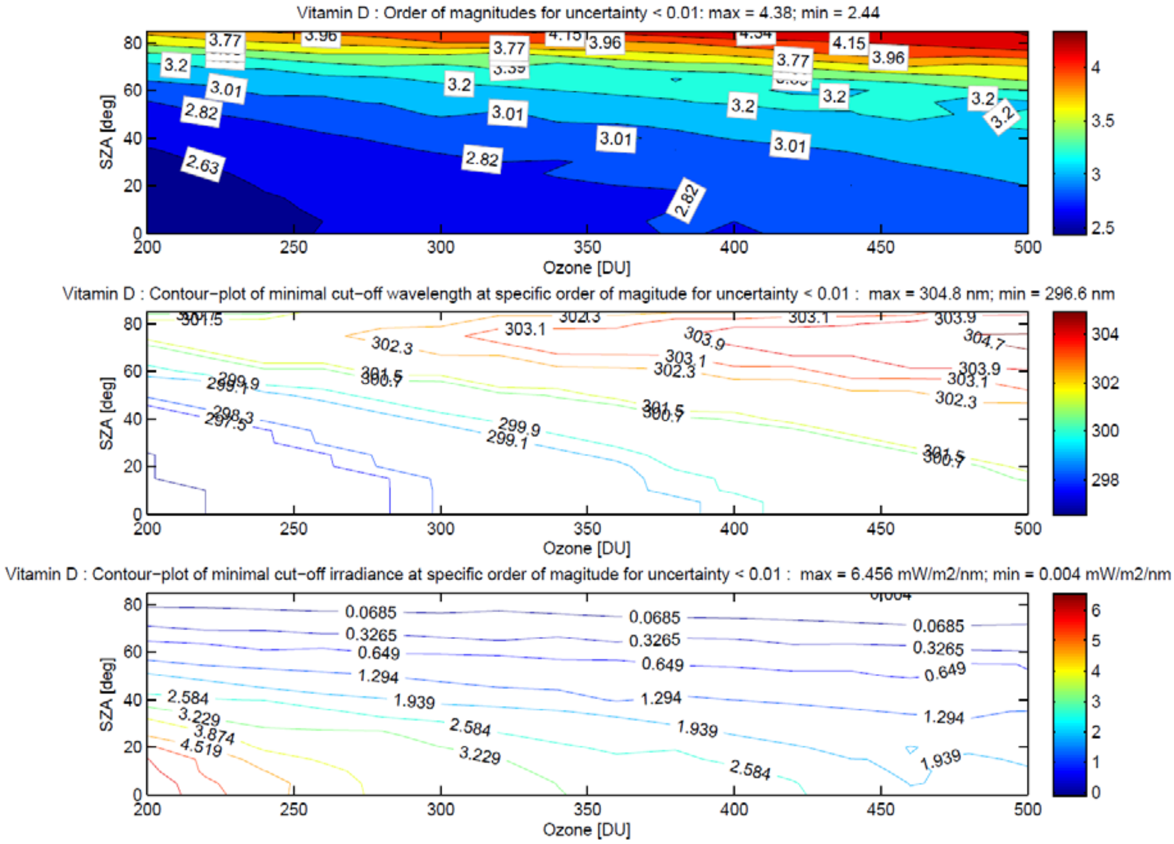

Figure A2: Vitamin D weighted dose rate for uncertainty < 1%: a) orders of magnitude (upper panel), b) minimal wavelength (middle panel) and c) minimal detection threshold of absolute irradiance (lower panel).

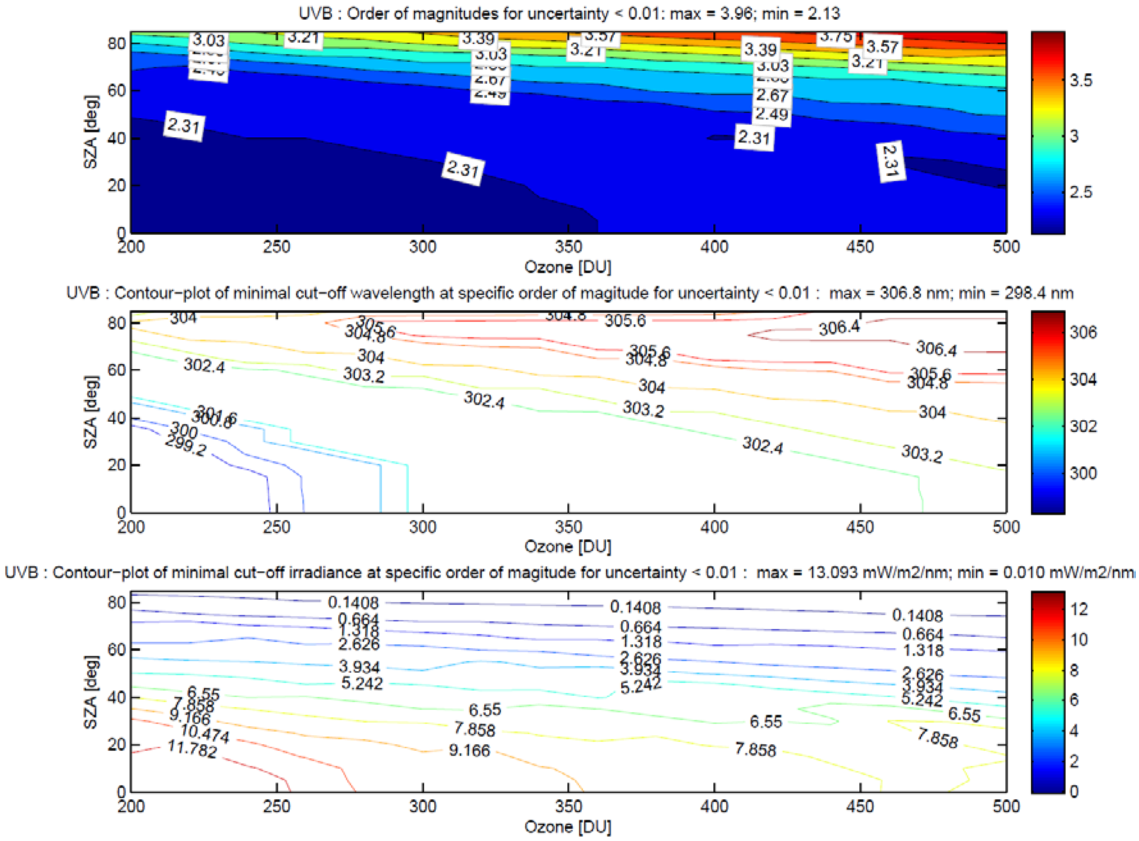

Figure A3: UVB for uncertainty < 1%: a) orders of magnitude (upper panel), b) minimal wavelength (middle panel) and c) minimal detection threshold of absolute irradiance (lower panel).

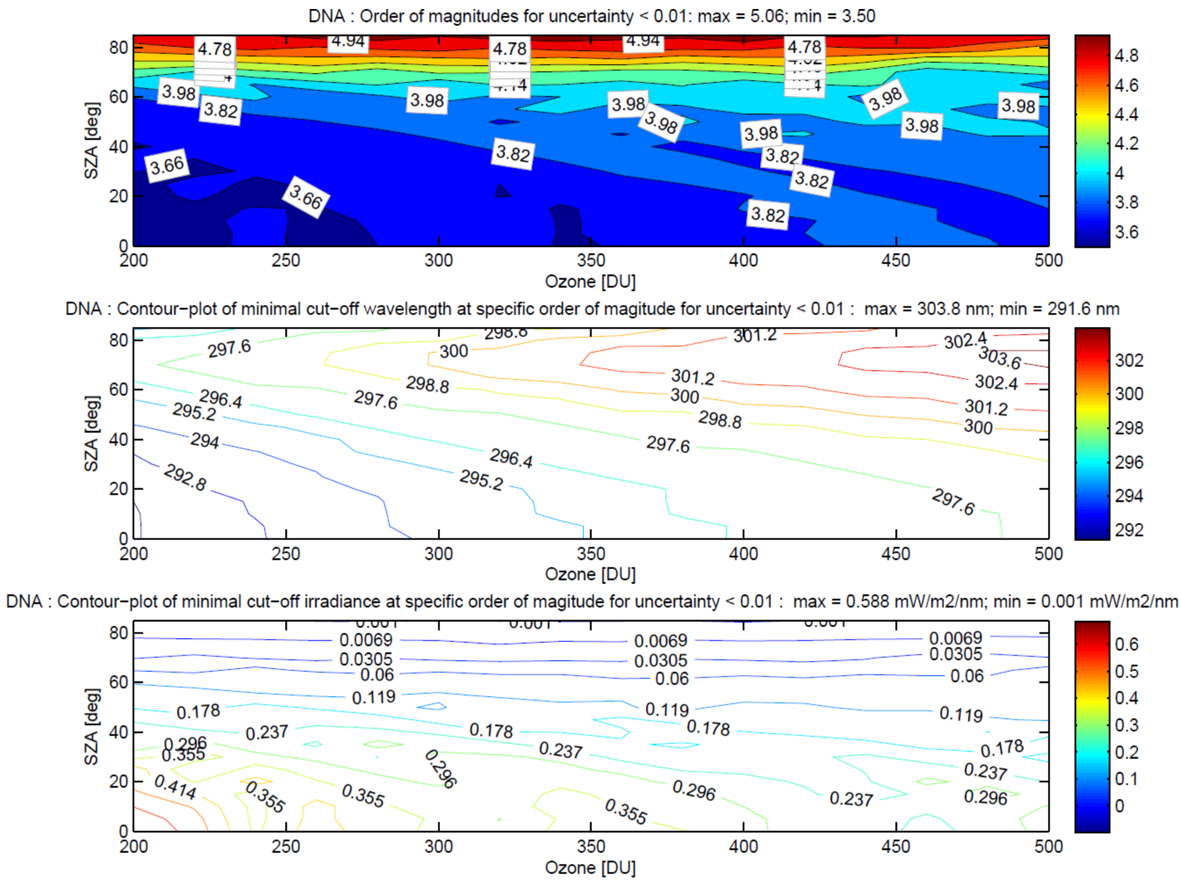

Figure A4: DNA weighted dose rate for uncertainty < 1%: a) orders of magnitude (upper panel), b) minimal wavelength (middle panel) and c) minimal detection threshold of absolute irradiance (lower panel).

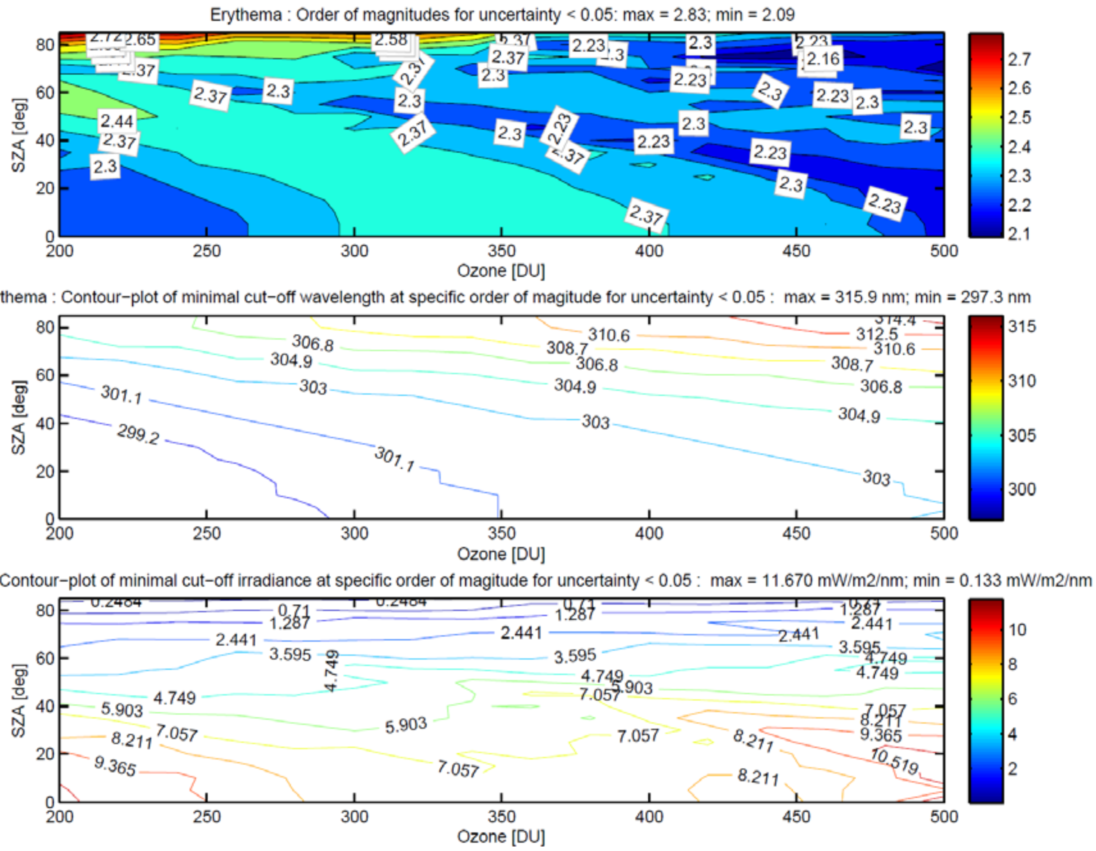

Figure A5: Erythema weighted dose rate for uncertainty < 5%: a) orders of magnitude (upper panel), b) minimal wavelength (middle panel) and c) minimal detection threshold of absolute irradiance (lower panel).

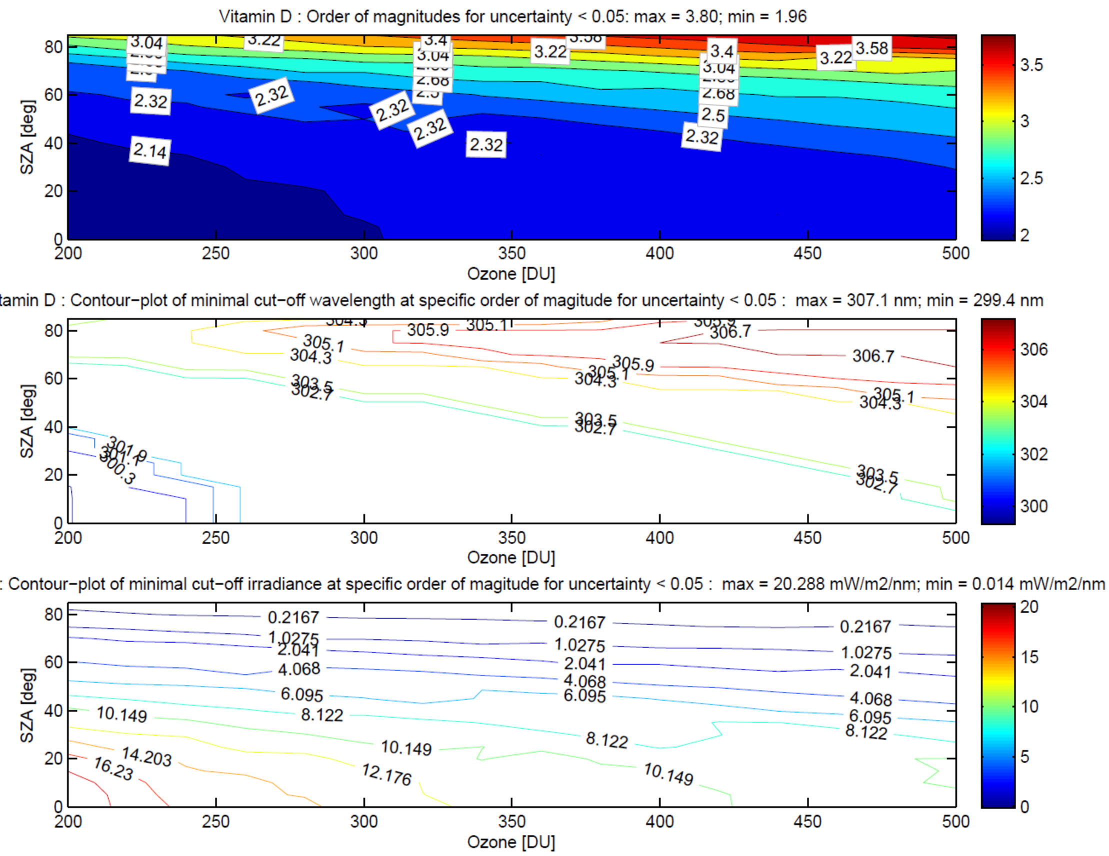

Figure A6: Vitamin D weighted dose rate for uncertainty < 5%: a) orders of magnitude (upper panel), b) minimal wavelength (middle panel) and c) minimal detection threshold of absolute irradiance (lower panel).

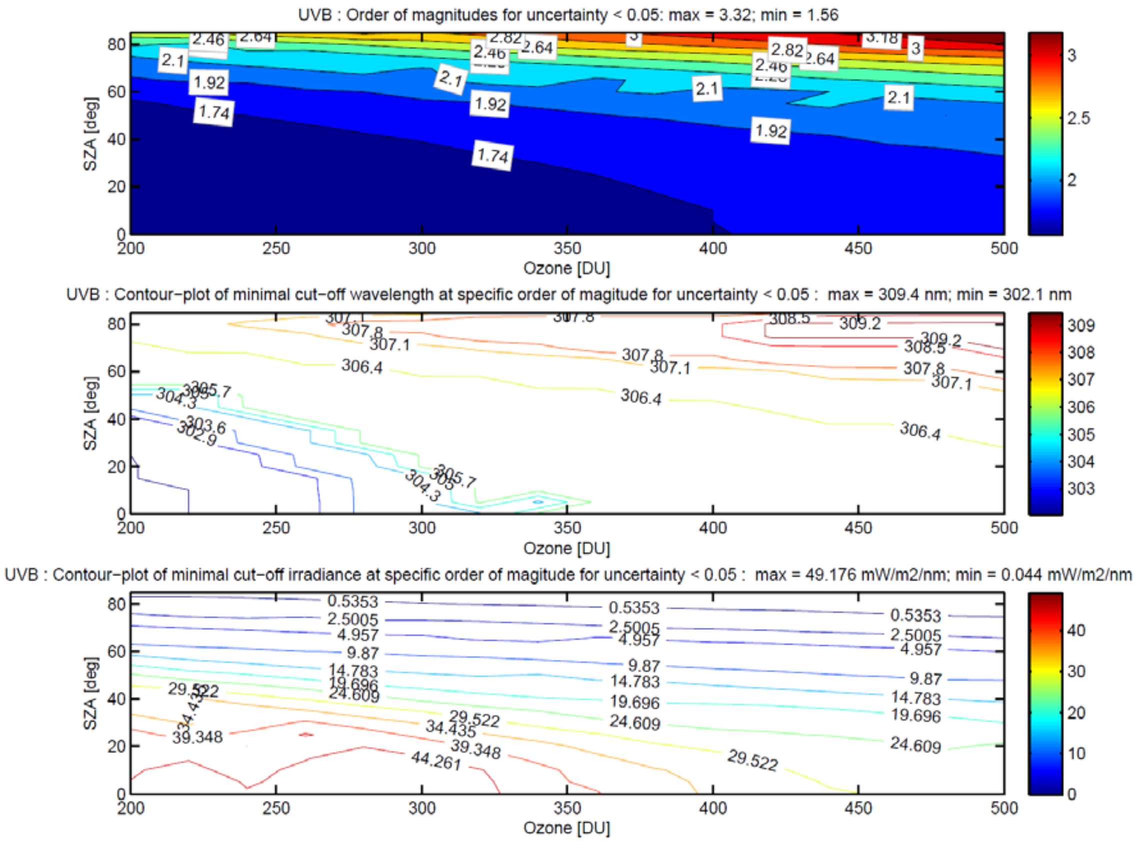

Figure A7: UVB for uncertainty < 5%: a) orders of magnitude (upper panel), b) minimal wavelength (middle panel) and c) minimal detection threshold of absolute irradiance (lower panel).

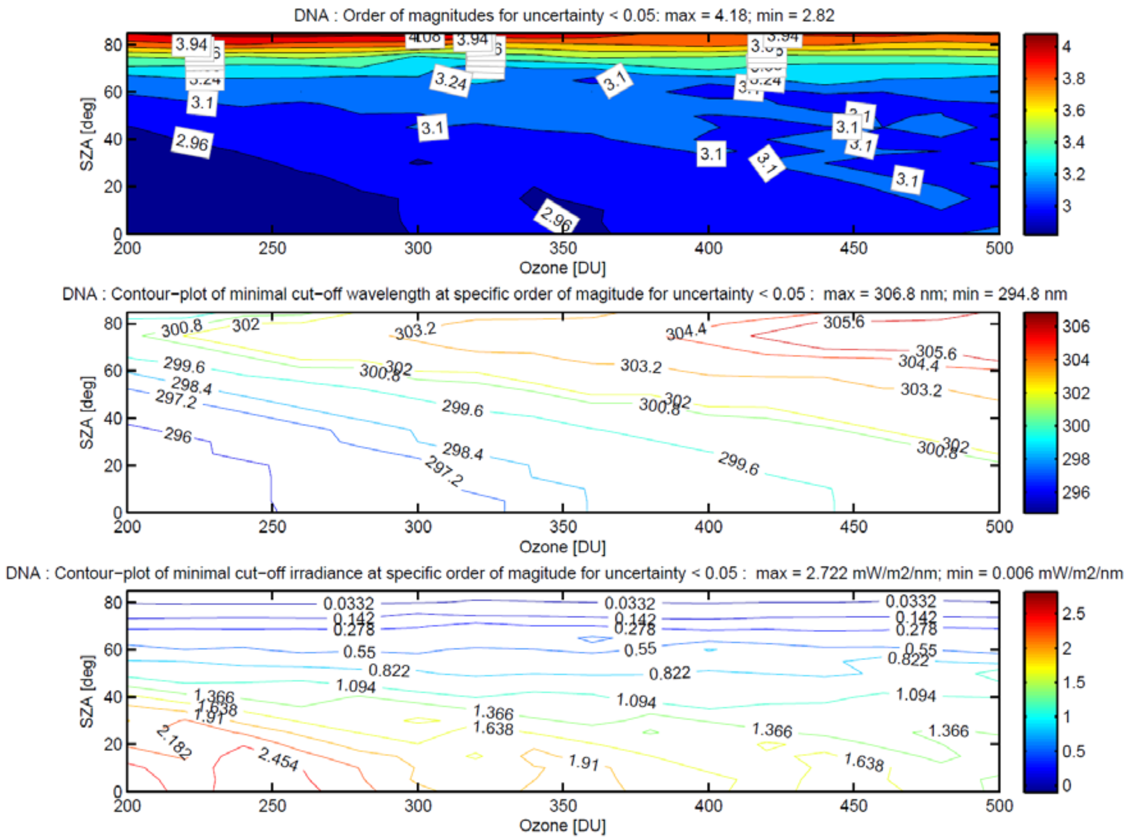

Figure A8: DNA weighted dose rate for uncertainty < 5%: a) orders of magnitude (upper panel), b) minimal wavelength (middle panel) and c) minimal detection threshold of absolute irradiance (lower panel).

Appendix B

Introduction

The objective of this sensitivity analysis is to investigate the impact of the uncertainty of solar UV irradiance measurements from array spectrometers on the following (most common) action spectra such as, CIE Erythema, Vitamin D3, Total UVB and DNA damage.

The main question is: What is the uncertainty of the weighted action spectra if the array spectrometer is able to detect global irradiance of 1 mW?

Dataset

The study was performed using model spectra obtained with the "LibRadtran" radiative transfer package[2] using as main variables the solar zenith angle (SZA) and the total column ozone (TO_3). The spectra were computed over the range 280 to 450 nm for the SZA range 0 to 85° and TO_3 from 200 to 500 nm. A total of 288 (=18 SZA x 16 TO_3) spectra were calculated.

Procedure

i) Irradiances below the critical minimum irradiance (*min_{irr} =1 mW)* and shorter than the wavelength *wl-cut* at *min_{irr}* were set to 0, assuming that measurements below this cut-off were not reliable.

ii) The spectra of both, the original data (obtained by the model) and the modified spectra as described in ii)-iii) were weighted with the action spectra for Erythema, Vitamin D3, UVB and DNA.

iii) From these weighted spectra the integral of irradiance between 280 and 450 nm was calculated for all SZA and TO_3. To estimate the fractional bias of the weighted spectra for all possible combinations of SZA and TO_3, the ratio between the original model data and the modified spectra was calculated as defined in following:

$$Fractional\ Deviation = \frac{TRUE}{\frac{Uncertain}{Measurement}} = \frac{\int_{280nm}^{450\ nm} E(\lambda, SZA, O3) * C(\lambda) d\lambda}{\int_{wl-cut}^{450\ nm} E(\lambda, SZA, O3) * C(\lambda) d\lambda} \qquad \text{(Eq. 3)}$$

Where $E(\lambda, SZA, O3)$ is a specific solar UV spectrum, $C(\lambda)$ denotes the normalized weighting function for the different action spectra (a-d) and *wl-cut* indicates the cut-off wavelength defined in ii).

[2] Mayer, B. and Kylling, A.: Technical note: The libRadtran software package for radiative transfer calculations - description and examples of use, Atmos. Chem. Phys., 5, 1855-1877, doi:10.5194/acp-5-1855-2005, 2005

Results

Figure B1 displays the cut-on wavelength for all conditions of SZA and TO_3 at 1 mW m^{-2} nm^{-1} of global irradiance.

The results of the achieved uncertainty depending on SZA and TO_3 for all combinations of SZA and TO_3, preconditioned that the instrument is limited to detect 1 mW m^{-2} nm^{-1}, is presented in Figure B1 to B4 for all 4 action spectra for uncertainties of 0.05 %, 1 %, 5 % and 10 %.

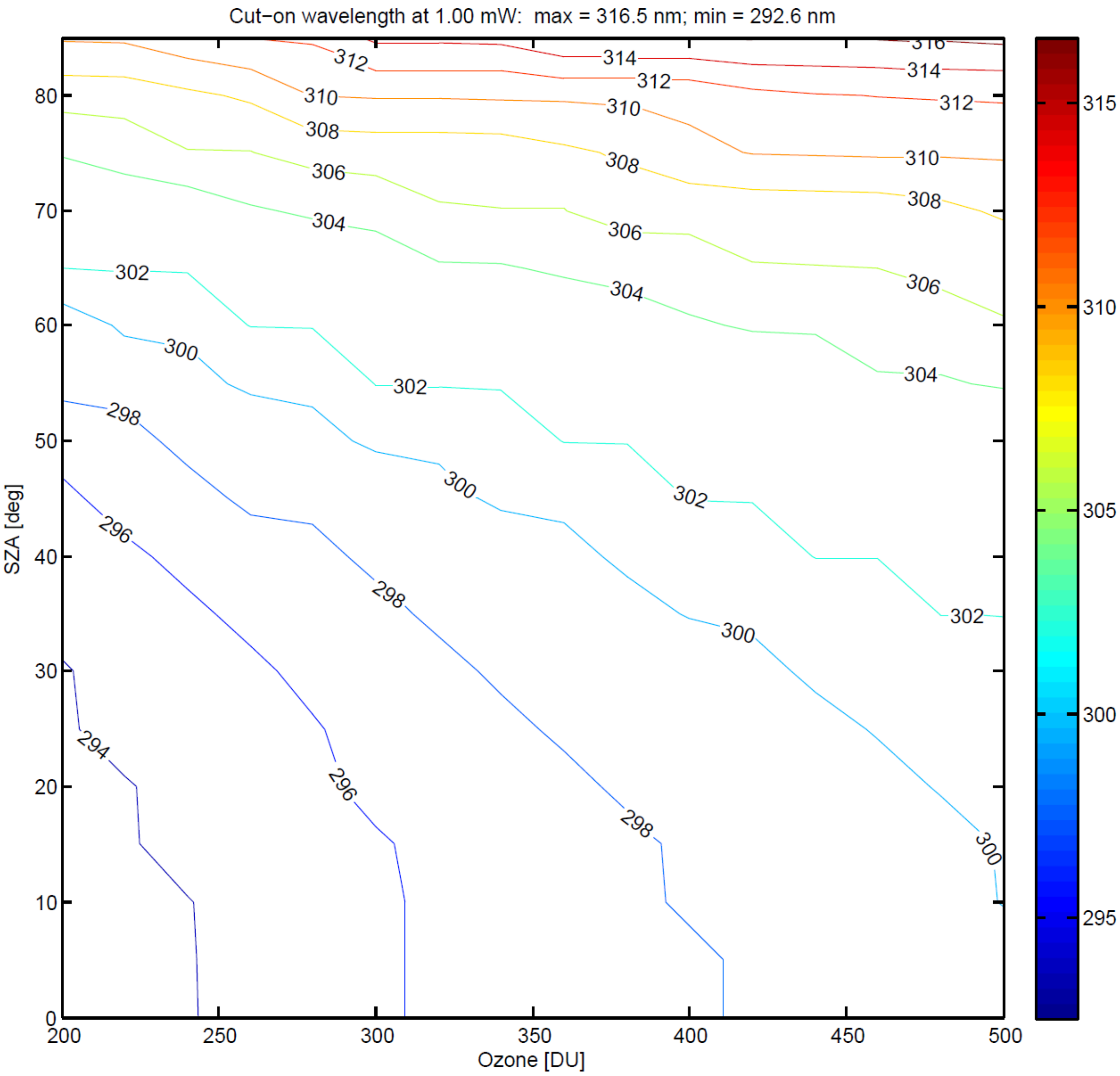

Figure B1: Cut-on wavelength at the detection threshold of 1 mW m^{-2} nm^{-1} global irradiance.

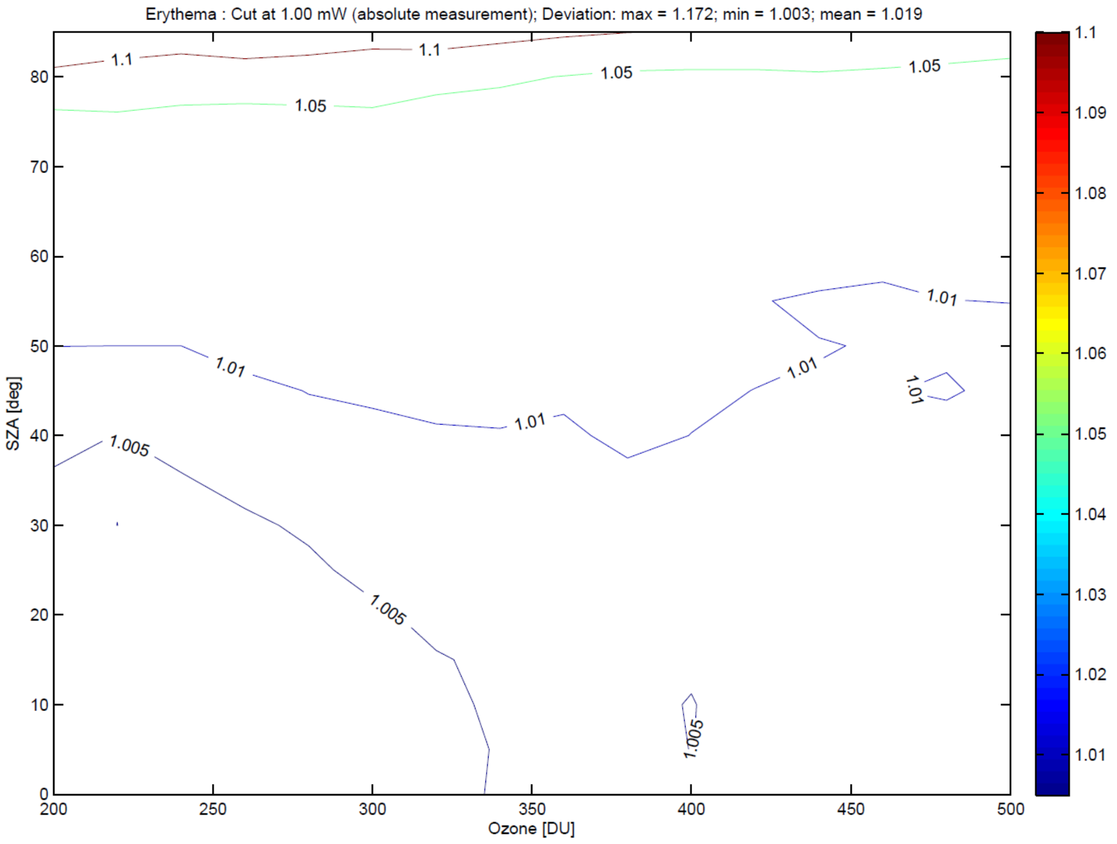

Figure B2: Erythema: Uncertainty of weighted dose rate if the instrument is limited of detecting 1 mW m^{-2} nm^{-1} global irradiance.

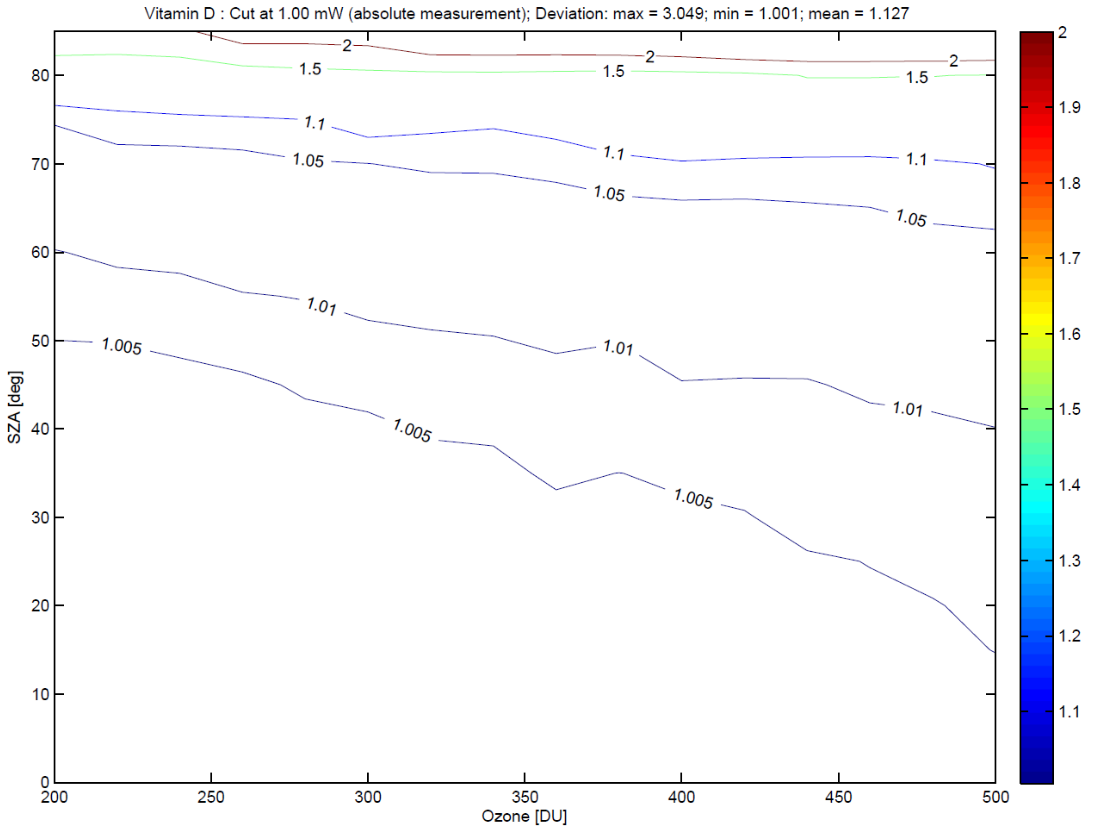

Figure B3: Vitamin D: Uncertainty of weighted dose rate if the instrument is limited of detecting 1 mW m^{-2} nm^{-1} global irradiance.

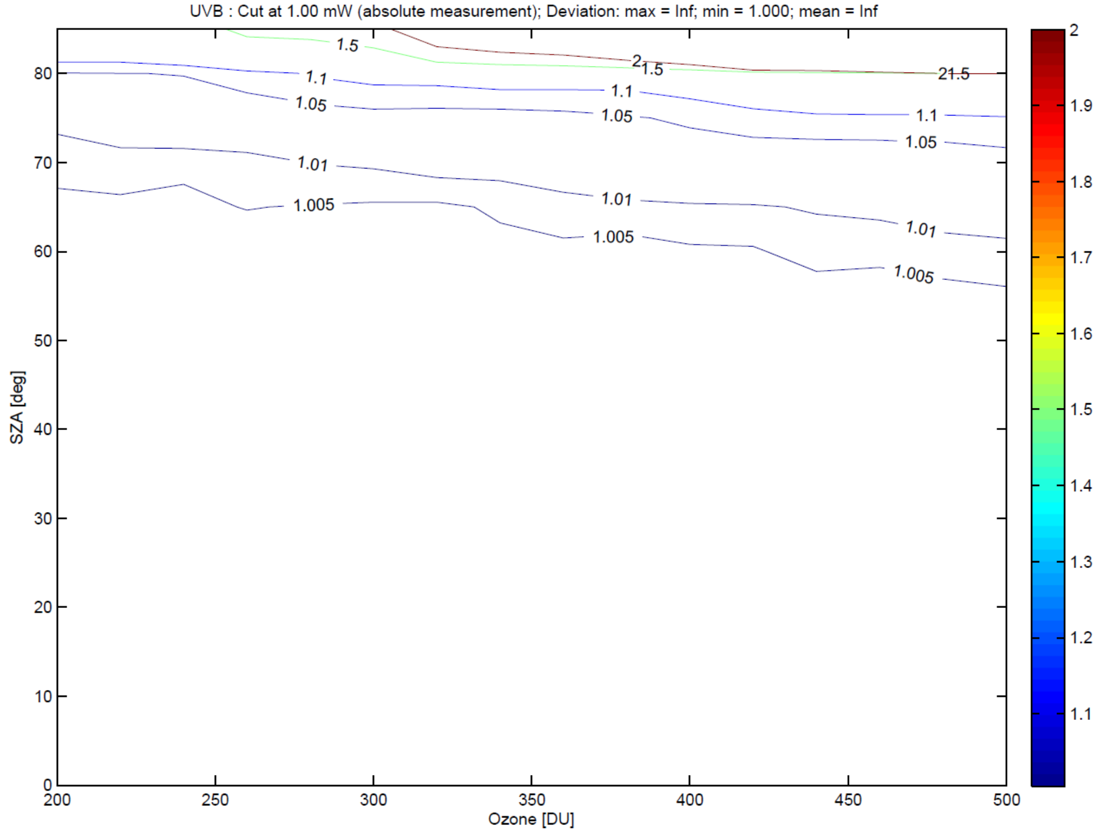

Figure B4: UVB: Uncertainty of weighted dose rate if the instrument is limited of detecting 1 mW m^{-2} nm^{-1} global irradiance.

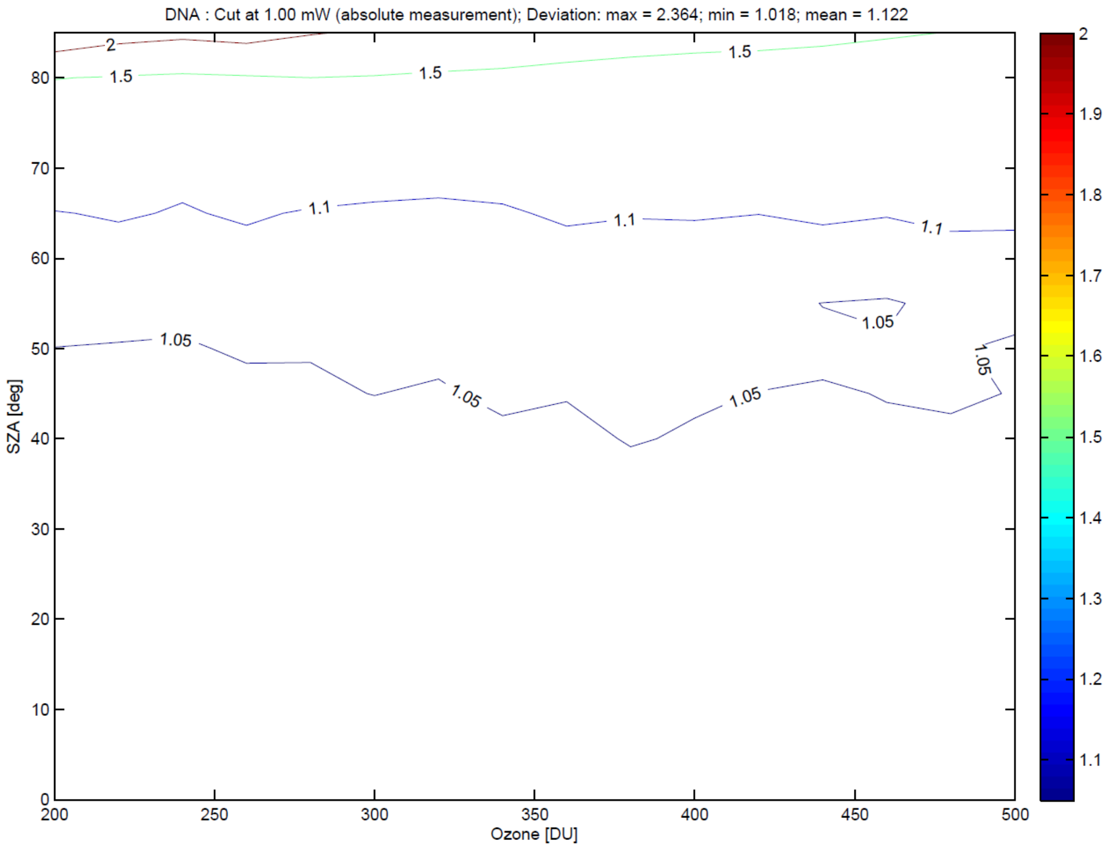

Figure B5: DNA: Uncertainty of weighted dose rate if the instrument is limited of detecting 1 mW m^{-2} nm^{-1} global irradiance.