Impact of dynamic range limitations on solar UV radiation weighted irradiances

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Introduction

Solar UV radiation has an influence on biological ecosystems and its measurement is in particular important for human health prevention. Shortwave radiation in a wavelength range between 280 to 400 nm interacts with the human body, generating e.g. sunburn on the skin or photokeratitis in the eye. UV radiation also causes DNA damage or produces Vitamin D3. The latter may have positive human health benefits.

In global solar UV radiation monitoring networks, broadband or filter radiometers are commonly used to derive the dose rate of UV radiation for biological purposes [1]. These instruments are typically optimized for one particular case (e.g. Erythema – Sunburn) or can be used for other biological applications with a limited accuracy. However, array spectroradiometers (ASRM) can measure an entire solar UV spectrum with a spectral resolution of less than a few nanometers, which enables to apply the data to different biological weighting functions (action spectra) to derive its dose rate. ASRMs are single monochromators, which are small, cost and maintenance effective and robust [2]. However, these instruments suffer from the impact of stray light in the one grating setup of the device and exhibit a limited detection threshold of the array detector [2]. A typical detection threshold for ASRM is quantified as about 1 $mWm^{-2}nm^{-1}$ [2, 3]. These limitations can lead to substantial biases of the UV measurement in particular in the UV-B range (280-315 nm). In order to describe methods for the practical operation of ASRMs measuring solar UV radiation a guideline was prepared within the EMRP project ENV03 ("Traceability for surface spectral solar ultraviolet radiation") and presented at the International Radiation Symposium (IRS) in August 2012 [3]. In this guideline the requirements of measuring solar UV with ASRM are summarized. The recommendations of the guideline are based among other investigations on a sensitivity study on potential biases from the ASRM measurements. This article aims to present and discuss the main part of the theoretical sensitivity analysis, which investigates the impact of the uncertainty of solar UV irradiance measurements from ASRM on the following action spectra:

- CIE Erythema (280 to 400 nm) [4]
- Vitamin D3 generation (280 to 330 nm) [5]
- Total UVB (280 to 315 nm)
- DNA damage (280 to 370 nm) [6]

The sensitivity analysis addresses the specific question: What is the required dynamic range in solar UV irradiance measurements to achieve an integration of a solar UV spectrum with a selected action spectrum within 1% of the full solar spectrum under clear sky conditions? Any uncertainty contributions from e.g. calibration, angular response, temperature and stability are explicitly excluded in this analysis. The dynamic range of solar UV measurement also determines the minimal wavelength (*wl-cut*) and minimum intensity (min_{irr}), defined by a signal to noise ratio of 1, which should be measured with ASRM to achieve an uncertainty of less than 1% of the weighted dose rates. The knowledge of these specific parameters is of practical interest to use ASRM for biological applications and the following results may lead to determine the applicability of a specific ASRM intended to be used to monitor solar UV radiation for human health prevention.

Data and Method

Modelled solar UV spectra were used for this study. The spectra were obtained with the "LibRadtran" radiative transfer package [7] assuming clear sky conditions. The main variables for the model calculations were the solar zenith angle (SZA) and the total column ozone (TO_3). A total of 288 (=18 SZA x 16 TO_3) spectra were computed over the wavelength range 280 to 450 nm for the SZA range 0° to 85° and TO_3 from 200 to 500 DU. Figure 1a shows 4 modeled spectra for the extreme cases of atmospheric conditions, while Figure 1b indicates the different biological weighting functions applied to the solar spectra.

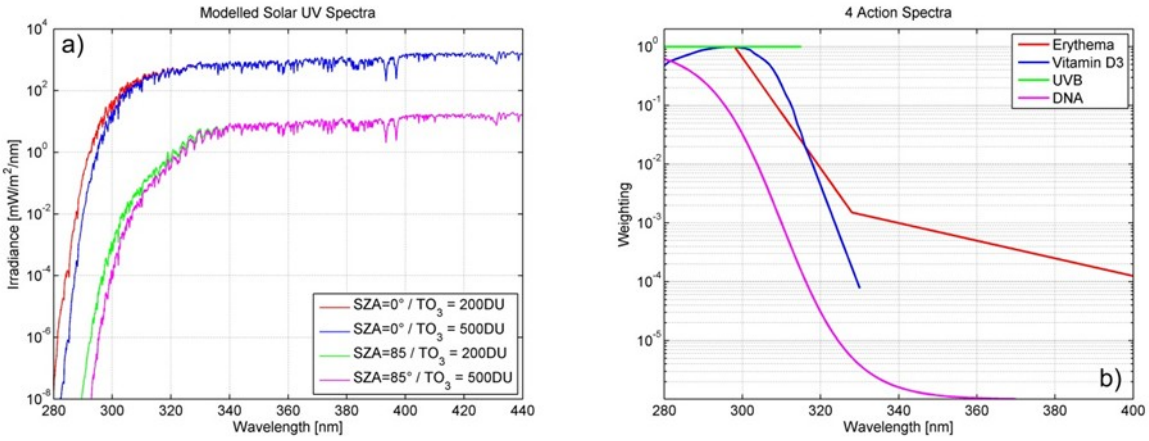

Figure 1. a) Modelled solar UV spectra for 4 different atmospheric conditions represented by the variable solar zenith angle (SZA) and total ozone column (TO_3). b) Four different action spectra used for the weighting of the solar spectra to calculate the integral value.

To calculate the minimum required order of magnitude of the dynamic range, the following procedure was applied:

1) The maximum irradiance (max_{irr}) of a specific modelled solar spectrum is determined. The order of magnitude is predefined as: $10^{\text{m-order}}$. From the ratio of these two values the minimum irradiance (min_{irr}) is calculated using equation 1, assuming that the ASRM is able to accurately measure the irradiance from the maximum intensity to the minimum intensity (min_{irr}):

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

2) It is further assumed that irradiances below the critical min_{irr} and shorter than the wavelength *wl-cut* at min_{irr} are not reliable due to the impact of stray light and poor detectability of the array detector (e.g. signal to noise lower or equal to one). Therefore these values are set to 0.

3) The obtained modified spectrum and the original modeled spectrum are weighted with the action spectra for Erythema, Vitamin D3, UVB and DNA (see Figure 1b) and the integral of the weighted spectra is calculated for all SZA and TO_3. The ratio between the original model data and the modified spectra is determined as

$$\text{Fractional deviation} = \frac{\text{Uncertain measurent}}{\text{TRUE}} = \frac{\int_{wl-cut}^{450nm} E(\lambda, SZA, O_3) * C(\lambda) d\lambda}{\int_{280nm}^{450nm} E(\lambda, SZA, O_3) * C(\lambda) d\lambda} \quad (2)$$

where $E(\lambda,SZA,O_3)$ is a specific modeled solar UV spectrum, $C(\lambda)$ denotes the normalized weighting function for the different action spectra (see Figure 1b) and *wl-cut* indicates the cut-off wavelength derived from min_{irr} as defined in 1). The fractional bias of the weighted spectra for all possible combinations of SZA and TO_3 was determined for different orders of magnitude (*m-order*).

4) With the procedure 1-3 the order of magnitude depending on all SZA and TO_3 combinations, was selected if the deviation is less than 0.01 (=1 %). This order of magnitude also defines the specific wavelength (*wl-cut*) and the corresponding minimum absolute irradiance where the weighted integral biases are <1%.

Results and Discussion

The procedure described above results in 3 different surface plots for each biological weighting function (Figure 2-5). The results reveal that the minimum required order of magnitude to achieve an uncertainty of the weighted integral of less than 1% varies significantly between all 4 weighting functions. The same procedure yields the cut-off wavelength and the corresponding minimum detectable intensity as a function of SZA and TO_3, assuming clear sky conditions.

a) Erythemal action spectrum

Theoretically, the minimum requirement for an ASRM to determine erythemal weighted global irradiance for all atmospheric conditions is the ability of the instrument to cover 3.74 orders of magnitude relative to the maximum irradiance intensity. Figure 2a indicates that this benchmark of 1% is reached under the extreme conditions at high zenith angles (~85°) and low TO_3 (~200 DU) concentrations. In this region the measurements below about 295 nm (see Figure 2b) can be set to 0 resulting in an integral percental bias of <1%. Figures 2b and 2c show that in priciple ASRM need to be able to measure irradiances of ~2.5 $mWm^{-2}nm^{-1}$ at 300 nm (for high SZA=85° and low TO_3=200 DU) and ~0.05 $mWm^{-2}nm^{-1}$ at 309 nm (for high SZA=85° and high TO_3=500 DU). Note that detecting 0.05 $mWm^{-2}nm^{-1}$ is a demanding requirement for the detectability of the detector in ASRMs [3].

However, an intensity of about 1 $mWm^{-2}nm^{-1}$ may be practically detected with typical array detectors by applying the procedure describes in the guideline [3]. This level of intensity is reached in case of lower SZA (< 50°) and for moderate concentrations of TO_3 (~350 DU) with a cut-off wavelength around 300 nm (Figure 1 b).

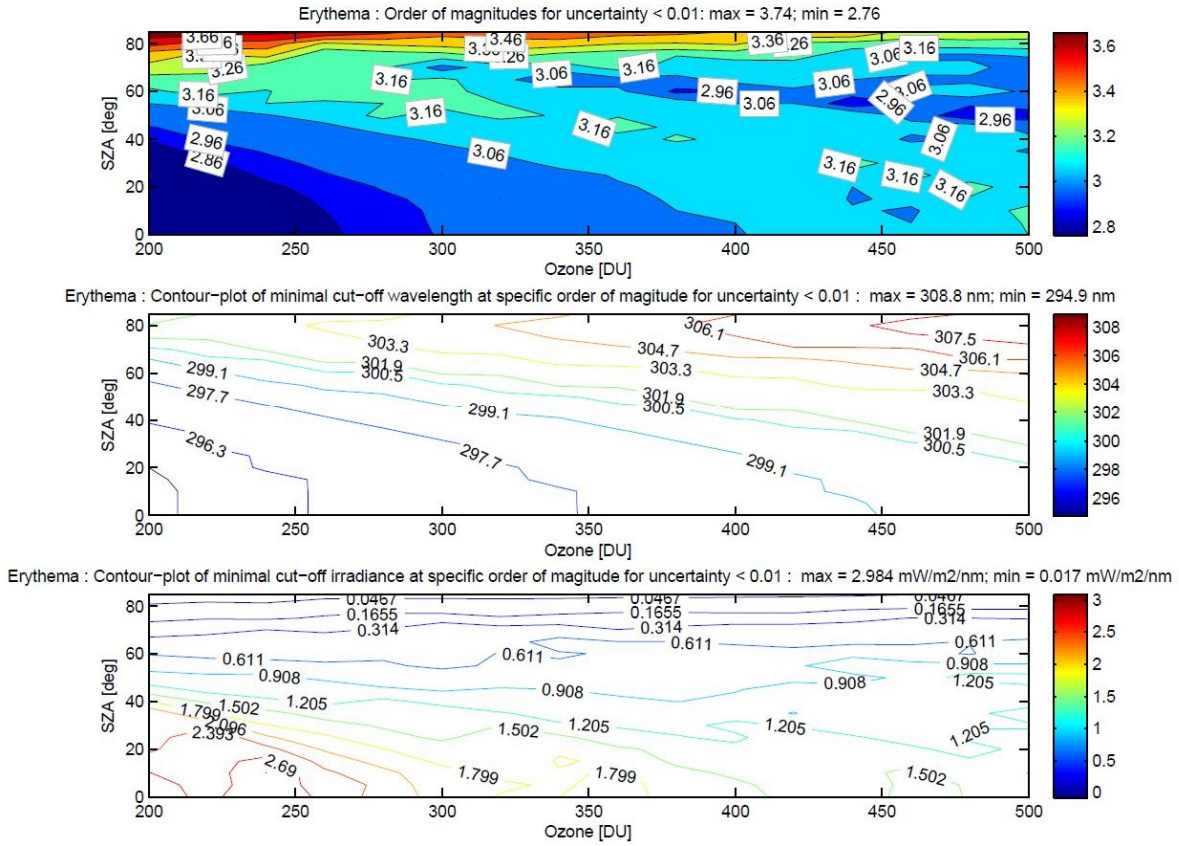

Figure 2 a-c. Erythema weighted dose rate for uncertainty < 1%: a) orders of magnitude (upper panel), b) minimal wavelength (middle panel) and c) minimal detection threshold of absolute irradiance (lower panel).

b) Vitamin D3 action spectrum

The minimum requirement for an array spectrometer is to cover 4.4 orders of magnitude when investigating Vitamin D3 related biological effects, which is more than half an order higher than required for erythemal weighted dose rates. Figure 3a demonstrates that due to the theoretical considerations the critical benchmark of 1% is also reached under the extreme conditions at high zenith angles (~85°) but in contrast to erythemal weighted global irradiance, at high TO_3 (=500 DU) concentrations. Remarkably, in this region the measurements below about 304 nm (see Figure 3b) can be set to 0, if the irradiance of ~0.005 $mWm^{-2}nm^{-1}$ can be measured with a signal to noise ratio of 1, which is very below a typical detection threshold of array detectors.

However, related to practice at SZA < 50° irradiance of ~1 $mWm^{-2}nm^{-1}$ can be measured at wavelengths around 300 nm. The required level of intensity is almost independent on the TO_3 concentration (200-500 DU). This irradiance can be detected with typical monochromators presumed that a stray light reduction until 300 nm can be achieved.

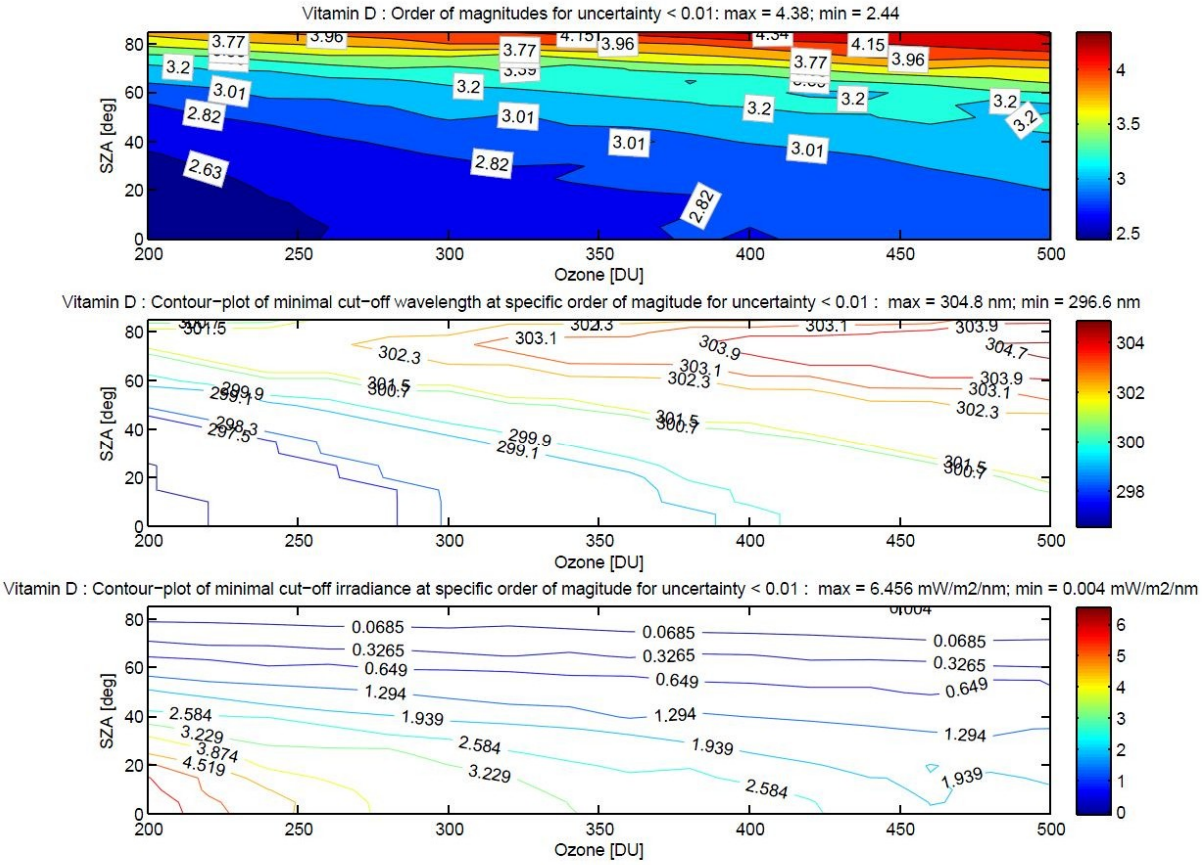

Figure 3 a-c. Vitamin D weighted dose rate for uncertainty < 1%: a) orders of magnitude (upper panel), b) minimal wavelength (middle panel) and c) minimal detection threshold of absolute irradiance (lower panel).

c) Total UVB global Irradiance

To accurately estimate the total UVB, an ASRM should cover at least 3.95 orders of magnitude of the dynamic range of the UV-irradiance for all atmospheric conditions and SZA. Figure 4a show that similar to Vitamin D3 the benchmark of 1% is reached under the extreme conditions at high zenith angles (~85°) and high TO_3 (=500 DU) concentrations. In this region the measurements below about 306 nm (see Figure 4b) can pragmatically be set to 0 to reach the predefined accuracy.

In contrast to Erythema and Vitamin D3 the fractional deviation of the weighted integral is less than 1% for SZA < 70° if the irradiance can be accurately measured at a level of 1 $mWm^{-2}nm^{-1}$. This means that it is practically feasible to measure accurate total UVB for SZA below 70°, where only around 2.5 orders of magnitude have to be captured at a wavelength around 303 nm. Therefore the requirements to operationally estimate total UVB global irradiance is less demanding then for Erythema or Vitamin D3.

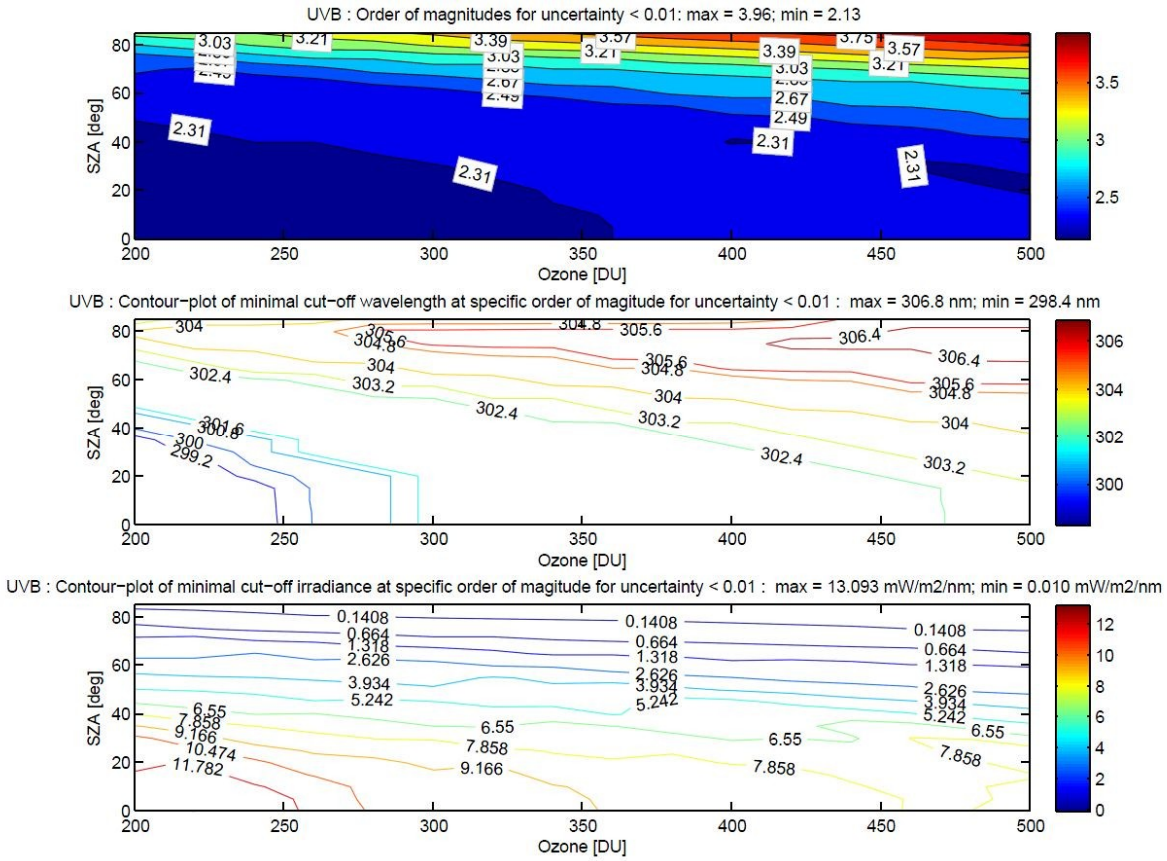

Figure 4 a-c: UVB weighted dose rate for uncertainty < 1%: a) orders of magnitude (upper panel), b) minimal wavelength (middle panel) and c) minimal detection threshold of absolute irradiance (lower panel).

d) DNA

Considering DNA weighted solar UV irradiance, the ASRM should cover in principle about 3.5 – 5 orders of magnitude of the dynamic range for integral fractional biases of less than 1% (Figure 5a). Covering such a high order of magnitude, the cut-off wavelength varies from 290 nm to 302 nm (Figure 5b), which is significantly below the wavelength found in the first 3 cases. Also differently to all others biological weighting functions, Figure 5c indicates that the required detection threshold varies between 0.001 – 0.5 $mWm^{-2}nm^{-1}$, which is a very challenging requirement for typical array detectors, even if a stray light reduction until 3.5-5 orders of magnitude can be achieved.

If an intensity ~0.3 $mWm^{-2}nm^{-1}$ can be detected practically by a specific instrument and procedure (e.g. with cooled array detectors), the DNA weighted integral is less than 1% at SZA around noon (SZA ~20°). In this case the required orders of magnitude and the minimal intensity are weakly correlated with TO_3 concentration in the atmosphere, but the signal should be accurately detected to wavelength between 293 – 298 nm.

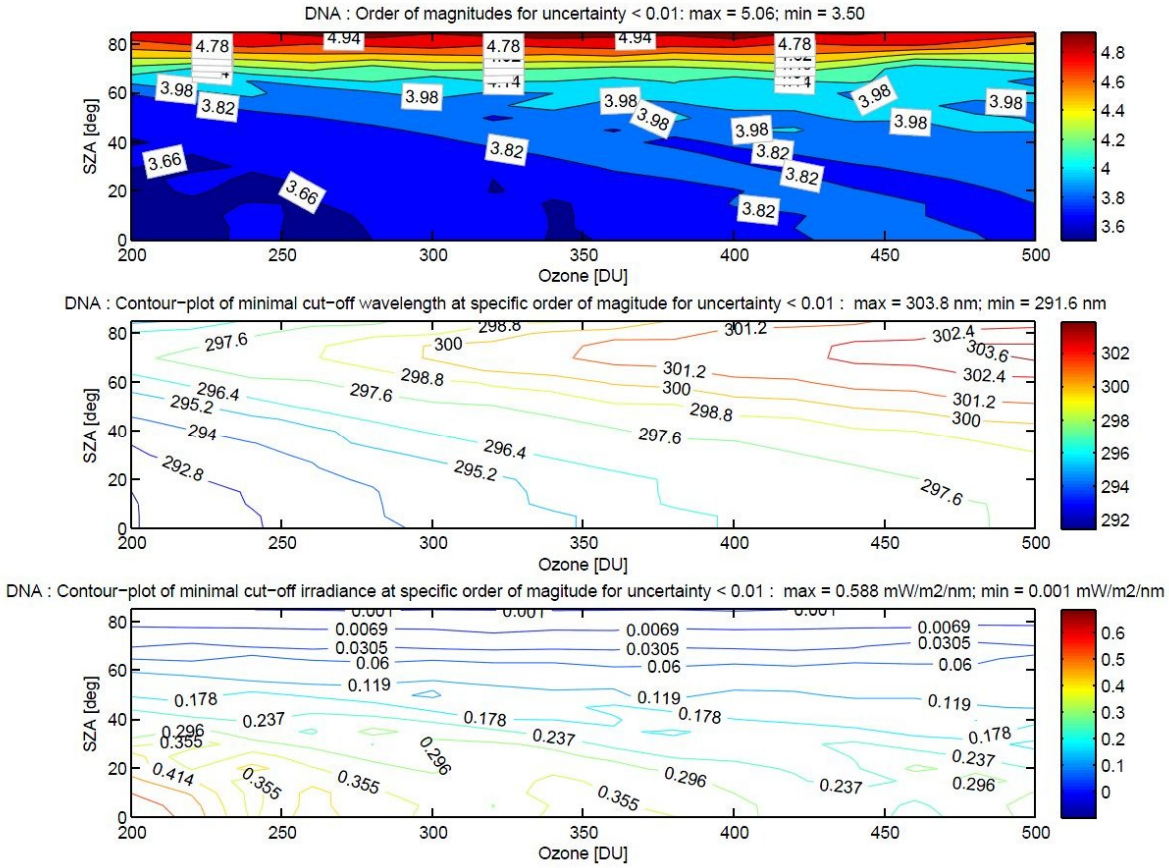

Figure 5 a-c: DNA weighted dose rate for uncertainty < 1%: a) orders of magnitude (upper panel), b) minimal wavelength (middle panel) and c) minimal detection threshold of absolute irradiance (lower panel).

Conclusion

For spectrally weighted solar irradiances, such as Erythema, Vitamin D3, UVB or DNA action spectra, at least 3.8 – 5 orders of magnitude of the dynamic range of solar UV irradiance should be theoretically captured by array spectrometers if an accuracy of 1% should be achieved at all atmospheric conditions. The resulting orders of magnitude imply that a stray light reduction of the array spectroradiometer until wavelength between 290 to 298 nm with an irradiance detectability of 0.001 – 0.017 $mWm^{-2}nm^{-1}$ should theoretically be achieved for all SZA and TO_3 concentrations.

However, practically assumed that an array spectroradiometer is able to detect an intensity of around 1 $mWm^{-2}nm^{-1}$ with a signal to noise ratio of 1, the factional biases of the weighted integral are less than 1% for SZA smaller than 60° (Erythema, Vitamin D3, UVB-Index) and are less dependent on TO_3 concentration than on SZA. Under the condition of small SZA the irradiance of 1 $mWm^{-2}nm^{-1}$ is typically reached around 300 nm where the solar UV measurement should not be influenced by stray light in the instrument.

However, due to the considerations above we cannot assume that detecting 1 $mWm^{-2}nm^{-1}$ is sufficient to obtain DNA weighted integrals with an accuracy < 1%. To practically estimate the potential of DNA damage with solar UV radiation, require instrumentations which are highly sensitive and perform a stray light reduction to cover at least 4-5 orders of magnitude of the dynamic range.

Acknowledgement. This report was compiled within the EMRP ENV03 Project "Traceability for surface spectral solar ultraviolet radiation." The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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