Tethys
Journal of Mediterranean Meteorology & Climatology

Tethys 2011, **8**, 13–20
www.tethys.cat
ISSN-1697-1523
eISSN-1139-3394
DOI:10.3369/tethys.2011.8.02
Journal edited by **ACAM**

Estimation of the integrated UV erythemal radiation incident on vertical planes with the SMARTS2 model

G. Derouet[1], **M. P. Utrillas**[1], **V. Estellés**[1], **A. R. Esteve**[1], **M. J. Marín**[2], **J. L. Gómez-Amo**[1] **and J. A. Martínez-Lozano**[1]

[1]Solar Radiation Group, Earth Physics and Thermodynamics Department, Universitat de València, Dr. Moliner 50, 46100 Burjassot, Valencia

[2]Department of Mathematics for Economy and Management, Universitat de València, Avda. Tarongers s/n, 46022 Valencia

Received: 17-V-2010 – Accepted: 29-IX-2010 – **Translated version**

Correspondence to: jmartine@uv.es

Abstract

The SMARTS2 model has been used to estimate UV erythemal radiation (UVER) integrated on a horizontal plane and on vertical planes oriented north and south. The values obtained using the model were compared with experimental data provided by three radiometers YES-UVB-1located on these planes. To quantify the results, the statistical parameters considered were mean deviation, mean absolute deviation and root mean square deviation (RMSD). The results on a horizontal plane show RMSD values of about 10%, when working with aerosol optical depth at 500 nm, and 16% when working with the Ångström β coefficient. As for the results obtained for the north and south planes, these reach very high errors. The RMSD in these cases is 20.5% for the south plane and 32.5% for the north plane, in the most favorable of cases, when there are optical depth values to quantify the load of aerosols. These results do not improve even considering an annual trend, taking into account the different seasons, nor considering different periods throughout the day. We therefore consider that the SMARTS2 is not suitable for estimating the UVER incident on inclined planes.

Key words: UV erythemal radiation (UVER), vertical planes, SMARTS2 model

1 Introduction

The effect of ultraviolet radiation on living organisms has attracted the attention of researchers in the last thirty years (Frederick and Lubin, 1988; Scotto et al., 1988), leading to recommendations on exposure to UV rays in order to avoid acute or chronic damage (WMO, 1998; ICNIRP, 2004). Of all the effects that UV radiation has on human beings, the most common is erythema, or sunburn. In 1987 the *Commission Internationale de l'Éclariage* (CIE, 2000) adopted a standard erythema curve (McKinlay and Diffey, 1987) that is recommended to determine UV erythemal radiation (UVER). This UVER is calculated by weighting the standard erythema curve given by the CIE (also called erythemal action spectrum) with the incident solar radiation at ground level.

Measurements of the incident erythemal irradiance on a horizontal surface are not, however, the most appropriate method to estimate the actual dose received by human beings. The calculation of UVER radiation on inclined surfaces is essential for dosimetric studies. Unfortunately, there are few records of UVER measurements in planes other than horizontal, although some studies have shown that the global UVER incidence on a plane perpendicular to the sun becomes 27% higher than the incidence of UVER on a horizontal plane (Parisi and Kimlin, 1999). Webb et al. (1999) made measurements of spectral UVER on vertical planes for different azimuthal planes throughout one day (August 18, 1995). The influence of topography and soil reflectivity have also been studied by Weihs (2002), who found that in some specific topographical conditions, the incident intensity on inclined planes can be greater than on horizontal surfaces.

Given this lack of experimental data the use of models to estimate the incidence of UVER on inclined planes becomes necessary. These models are based on different approaches to solve the radiative transfer equation in the atmosphere. They can be multiple or single scattering models. Multiple scattering models, as their name implies, consider a multidispersive atmosphere, and usually resolve the radiative transfer equation by using the discrete ordinate model DISORT (Chandrasekhar, 1950). Some models of this type, in the UV range, are the SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer) (Ricchiazzi et al., 1998) or the UVSPEC (UV Spectral) (Meyer et al., 1997).

Single scattering models, also called fast spectral, consider that the atmosphere consists of a single layer, ie, it is vertically and horizontally homogeneous, and only single scattering occurs within it. An example of such models is the SMARTS2 (Simple Model of the Atmospheric Radiative Transfer of Sunshine) (Gueymard, 1995; 2005a), which also has the option of providing spectral UVER directly on a horizontal plane. This model has been used in the past by the authors to estimate global spectral radiance on a horizontal plane (Utrillas et al., 1998). In this paper this model has been used to estimate spectral UVB incidence on two vertical planes, north and south, over a year. Later this UVB is weighted with the erythemal action spectrum to obtain the spectral UVER. Finally the spectral irradiance is integrated to provide integrated UVER values on vertical surfaces.

Recently, the Solar Radiation Group of Valencia has set up a UVER measuring station integrated in the Faculty of Physics (Utrillas et al., 2009). Experimental data from this station have been used to validate the values estimated with the SMARTS2. The mean deviation (MBD), the mean absolute deviation (MAD) and the root mean square deviation (RMSD) have been taken as statistical indicators of the accuracy of the estimate.

2 The SMARTS2 model

The SMARTS2 model is a single scattering model developed in FORTRAN language, of open access (http://www.nrel.gov/rredc/smarts/). It calculates the direct and diffuse spectral irradiance on both horizontal and inclined planes. It is limited to clear days, not admitting the possibility of introducing cloudiness. The version used in this work, SMARTS2.9.5 provides an interface that allows the user to choose easily among ten types of standard atmosphere, or a type defined by the user. The model has spectral albedos, as well as data from the absorption coefficients of the main atmospheric components. It offers the possibility of calculating integrated measurements of the full spectral range of solar radiation (between 280 and 4000 nm), erythemal dose, UV index and other measurements weighted with different action spectra. It has up to seven extraterrestrial spectra proposed by different authors and one proposed by the author of SMARTS2 model (Gueymard, 2005b), which is a combination that includes those most used in the references.

This model is characterized by the multitude of options considered in the input parameters. As an example it must be noted that it proposes up to nine different models of aerosols: the four types proposed by Shettle and Fenn (1979), and the five proposed by the Standard Radiation Atmosphere (WMO, 1986). For more information about the SMARTS2, the user's manual can be consulted (Gueymard, 2005b).

Table 1. Monthly values of the aerosol optical depth (AOD) at 500 nm and of the Ångström β coefficient used.

Month	AOD (500 nm)	Ångström β
January	0.127	0.050
February	0.128	0.051
March	0.103	0.044
April	0.129	0.053
May	0.193	0.104
June	0.187	0.069
July	0.231	0.101
August	0.208	0.092
September	0.199	0.091
October	0.274	0.177
November	0.095	0.040
December	0.086	0.041

3 Experimental devices

To study the effects of UVER irradiance on planes other than the horizontal, a measurement station has been designed and installed at the Faculty of Physics of Valencia, which has six broadband UVB-1 YES radiometers. The measurements were done on the Campus of Burjassot (Valencia), which is located at latitude 39.5°N, longitude 0.418°W and at 40 m above sea level, and where the horizon obstacles do not exceed the altitude of 4°, with the exception of a small band in the northwest (Esteve et al., 2006). One of the radiometers measures the global UVER on the horizontal plane. Another one is coupled to a shadow band anchored in arms whose inclination is equal to the latitude. This band blocks direct sunlight from falling on the detector wich measures diffuse irradiance on the horizontal plane (Utrillas et al., 2007). The other four remaining instruments take measurements of global irradiance on vertical planes in the directions north, south, east and west (Figure 1). In this work only the measurements obtained with two of these four radiometers, those oriented toward north and south, have been used. Figure 2 shows the evolution of the values of the UVER at 12 GMT incident on the horizontal plane and on the north and south vertical planes, for the measurement period considered (2008).

The YES UVB-1 is a broadband radiometer, whose spectral range is 280-400 nm. It uses colored glass filters and a UVB-sensitive phosphor. Visible light, except for a small fraction in the range of red light, is absorbed by a first filter, a black glass which transmits only UV. The light transmitted by the filter falls on the phosphor, which is sensitive to UVB. This material absorbs the UVB component and reemits this light into visible light, predominantly at wavelengths corresponding to green. A second green glass filter lets the fluorescent light from the phosphor through while it absorbs the red light that may have been transmitted through the first

Figure 1. Experimental device for the measurement of ultraviolet erythemal radiation (UVER) on vertical planes (partial view).

black filter. The fluorescent light intensity is measured by a solid state photodiode.

The output of the YES-UVB-1 is an analog signal in volts. To convert it to irradiance units, a conversion factor is used, which is given by the quotient of the energy measured by a detector with an ideal spectral cosine response and the energy measured by the UVB-1. In practice, this factor is determined by the quotient between total UVB irradiance and the value of the output signal of the UVB-1 instrument at the measurement time. This conversion factor depends on the spectral range considered and the zenith angle.

The spectral response of the instrument may change over time, varying the transmittance of the first filter, so it is necessary to recalculate the conversion factors. This is actually a recalibration of the instrument and it is performed regularly. The YES UVB-1 radiometers used for the UVER measurements of this work are calibrated annually in the Atmospheric Sounding Station "El Arenosillo" belonging to the INTA (National Institute of Aerospace Technology), under the Ministry of Defense. This calibration involves laboratory actions and field measurements, making an analysis of the deviation of the erythemal action spectrum of the CIE, and an intercomparison with a Brewer spectroradiometer (Vilaplana et al., 2006).

Firstly, the relative spectral response of the radiometer (RSE) is measured in order to compare it with the response of the erythemal spectrum of the CIE, so that an ideal response would be one where the quotient between both of them is the unit. The matrix given by Equation 1 quantifies the extent to which the irradiance, weighted by the RSE of the instrument, is deviated from the erythemal irradiance, weighted by the erythemal action spectrum of the CIE according to the solar zenith angle and the total content of ozone.

The spectral irradiance (I) needed to find such a matrix is obtained with the radiative transfer model TUV (Tropospheric Ultraviolet and Visible Radiation Model) (Madronich, 1987).

$$ADA(\theta, O_3) = \frac{\int_\lambda I \cdot CIE \cdot d\lambda}{\int_\lambda I \cdot RSE \cdot d\lambda} \quad (1)$$

Secondly, an intercomparison is performed outdoors with the spectroradiometer Brewer MKIII#150. This intercomparison shows that the radiometer signal is proportional to the integrated irradiance of the spectroradiometer, which will allow us to calculate UV erythemal radiation. The final result is another matrix (Figure 3), which depends on the solar zenith angle and the total ozone column.

This reduces the cosine error of the measurements to a maximum of 4.2%. This characterization of the cosine error is included in the radiometer calibration matrix. Thus, the uncertainty related to the angular error in the radiometer measurements transformed into physical units by this matrix will be in all cases less than 4.5%.

To determine the optical depth of aerosols, a Cimel CE318 is used. This is a solar photometer designed for the autonomous and automatic measurement of direct and sky solar radiance, which became the standard of the AERONET network (Holben et al., 1998) for the measurement of aerosols. The photometer consists essentially of: a) an electronic control box, b) a robot, consisting of two electric motors controlling the azimuth and zenith coordinates, and c) a head plus some collimators. The sensor head is in turn equipped with a double collimator with a 1.2° angle of view (Field of View, FOV).

The sensor system is made up of two silicon photodiodes dedicated to the measurement of direct and sky radiance. The selection of wavelengths is done through interference filters inserted into a filter wheel with up to nine positions. The basic wavelengths are 440, 670, 870, 940 and 1020 nm, the bandwidth or Full Width at Half Maximum (FWHM) depends on the channel, although it varies between 2-40 nm depending on the region of the spectrum (Estellés et al., 2007).

4 Methodology and results

The SMARTS2 model has been used to obtain five-minute values of horizontal global UVB, which is taken as a reference, and values of UVB on vertical planes oriented north and south. The frequency of these values is given by the frequency of our experimental values. It should be noted, as already indicated, that the SMARTS2 model does not calculate inclined integrated erythemal irradiance, but ultraviolet spectral values. These spectral UVB values are weighted with the curve of the erythemal action spectrum to obtain spectral UVER, and then integrated to calculate the integrated UVER. The model has been used only for clear days, because it does not consider cloudiness.

The vertical profile of a standard atmosphere model corresponding to the Mid-Latitude has been introduced in the al-

Table 2. Results of the comparison of the SMARTS2 model with the experimental values obtained for 2008 on the horizontal, north oriented and south oriented planes, using as aerosol input parameter: aerosol optical depth at 500 nm and Ångström β coefficient. N pairs of values were used in the comparison.

Aerosols	AOD at 500 nm			Ångström β		
Statistical indicator	MBD (%)	MAD (%)	RMSD (%)	MBD (%)	MAD (%)	RMSD (%)
Horizontal plane (N = 7312)	-0.8	6.9	10.3	-0.6	10.3	15.8
North plane (N = 7312)	-24.6	25.1	32.5	-23.5	25.8	33.4
South plane (N = 3346)	-5.9	14.9	20.5	-5.2	17.3	24.5

Table 3. Results of the comparison of the SMARTS2 model with the experimental values obtained for 2008 on the horizontal, north oriented and south oriented planes, according to the different seasons. Aerosol input parameter: aerosol optical depth at 500 nm and Ångström β coefficient. N pairs of values were used in the comparison. ($*$) No experimental data available.

	Aerosols	AOD at 500 nm			Ångström β		
	Statistical indicator	MBD (%)	MAD (%)	RMSD (%)	MBD (%)	MAD (%)	RMSD (%)
Summer	Horizontal plane (N = 2186)	4.3	8.7	11.9	7.4	13.3	20.1
	North plane (N = 2186)	-22.4	23.0	29.0	-17.1	25.1	31.0
	South plane (N = 1105)	1.4	14.6	19.7	4.7	19.1	27.2
Winter	Horizontal plane (N = 1570)	-6.1	6.4	7.3	-8.0	8.9	9.9
	North plane (N = 1570)	-28.3	28.3	31.8	-28.7	28.7	32.3
	South plane ($*$) (N = 0)	-	-	-	-	-	-
Spring and fall	Horizontal plane (N = 3556)	-2.7	6.1	9.5	-3.4	9.1	14.0
	North plane (N = 3556)	-25.4	25.8	33.7	-25.5	26.1	34.1
	South plane (N = 2240)	-9.4	15.4	21.2	-9.6	16.9	23.7

gorithm, alternating between its Winter (fall-winter) or Summer (spring-summer) version, which includes, for different heights, values of pressure, temperature and relative humidity. As a model of aerosols, based on the results previously obtained for Valencia (Utrillas et al., 1998), the values for the urban model (SU) of the Standard Radiation Atmosphere (SRA) have been used (WMO, 1986). These values have been normalized to the local characteristics through the optical depth of aerosols (AOD) at 500 nm or the value of the Ångström β coefficient provided by the Cimel CE318, located on the roof of Block C of the Faculty of Physics in Burjassot. Table 1 shows the monthly values of the optical depth of the aerosols at 500 nm and the Ångström β coefficient used. For ozone, the daily values of the OMI (Ozone Monitoring Instrument) sensor aboard NASA's Aura satellite were taken. As ground albedo, the measured value of 0.1 was used, previously obtained by the authors, for the UV range (Utrillas et al., 2010).

The values obtained using the model have been compared with the experimental data provided by three radiometers YES-UVB-1, located on the horizontal, vertical oriented north and vertical oriented south planes. These radiometers are in the same terrace as the Cimel radiometer. The data recorded on these three planes during clear days in 2008 were used to validate the model. To select these clear days, the modified clearness index k_t' was used; its advantage over the clearness index is that it reduces dependence on the solar zenith angle, and it is defined as (Pérez et al., 1990):

$$k_t' = \frac{k_t}{1.031 e^{-1.4/(0.9+9.4/m)} + 0.1} \qquad (2)$$

where k_t is the clearness index (I/I_0) and m is the optical mass. Data was chosen where $k_t' > 0.7$, which is a criteria usually used to select cloudless data (Serrano et al., 2010).

To quantify the results of the study the following statistical parameters were considered: relative mean deviation (MBD), relative mean absolute deviation (MAD) and root mean square deviation (RMSD). These are given by the equations:

$$MBD = 100 \frac{\sum_{i=1}^{N} (y_i - x_i)}{N \overline{x}} \qquad (3)$$

$$MAD = 100 \frac{\sum_{i=1}^{N} |y_i - x_i|}{N \overline{x}} \qquad (4)$$

$$RMSD = 100 \frac{\sqrt{\frac{\sum_{i=1}^{N} (y_i - x_i)^2}{N}}}{\overline{x}} \qquad (5)$$

Where:

- y_i = estimated value of i-th UVER
- x_i: experimental value of i-th UVER

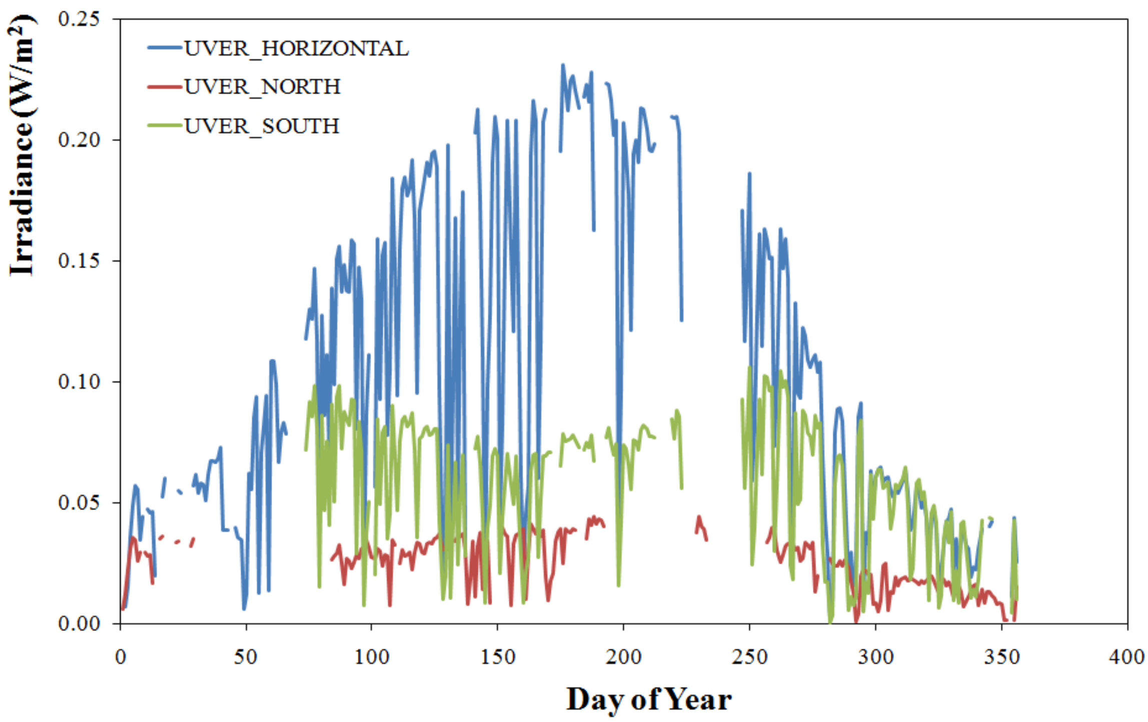

Figure 2. Evolution of the UVER values at 12 GTM, incident on the horizontal plane and on the north and south vertical planes for the considered measurement period (2008).

- $\overline{x}$: UVER daily average experimental value
- N: number of pairs of UVER values (experimental and estimated) used

The MBD, as well as the MAD and the RMSD thus defined are dimensionless and are expressed in %. Table 2 shows the results corresponding to five minute data throughout the considered period (clear days of 2008), using both AOD at 500 nm as well as the Ångström β coefficient to quantify aerosols. The UVER results on a horizontal plane are useful as a comparison with the results previously obtained for global irradiance on a horizontal plane in the range of 300 nm to 1100 nm (Utrillas et al., 1998). In this case a RMSD of 5.4% (when working with aerosol optical depth at 500 nm) and of 6.4% (when working with the Ångström β coefficient) were obtained. In the UV range these errors are almost doubled, especially those related to the values obtained using the Ångström β coefficient. This is because the SMARTS2 does not work in an entirely appropriate way in the UV range, as indicated by its author, who considers that it introduces an error of 20% in that range (Gueymard, 1995). The reason for this difference in performance lies in the spectral range used here, which is only 280 to 400 nm. In this range the scattering becomes much more significant and therefore a more detailed characterization of aerosols is needed, in addition to having to take multiple scattering into account, which the SMARTS2 does not do because it is a single scattering model.

As for the results obtained for the north and south planes, both underestimate the incident UVER (negative MBD), with the errors for the north plane being much greater than those for the south plane. It is noteworthy that better results are obtained on all planes when using the 500 nm AOD than when using the Ångström β coefficient.

The results were grouped seasonally, once again taking into account the optical depth and Ångström β coefficient as an indicator parameter of the load of aerosols. Table 3 shows the results obtained in this group, which considers the values for summer, winter and spring-fall separately. It should be noted that the radiometer located on the south plane had a functioning problem in winter and there are not enough experimental data to obtain statistically significant values. The other values follow the same trends that were observed when considered together. On the horizontal plane there are RMSD values ranging between 7% and 12%, and the vertical planes show that, except for the south plane in summer, the model underestimates the experimental values, with RMSD values ranging between 29% and 34% for the north plane and between 20% and 21% for the south plane, considering for the simulation the aerosol optical depth at 500 nm. As before, the errors obtained using the Ångström β coefficient are significantly greater than those obtained using the AOD at 500 nm,

Table 4. Results of the comparison of the SMARTS2 model with the experimental values obtained for 2008 on the horizontal, north oriented and south oriented planes, according to the different seasons, for different periods of the day. Aerosol input parameter: aerosol optical depth at 500 nm and Ångström β coefficient. N pairs for values used in the comparison. ($*$) No experimental data.

	Period	10 h to 14 h UTC			Before 10 h UTC			After 14 h UTC		
	Aerosols	AOD at 500 nm			AOD at 500 nm			AOD at 500 nm		
	Statistical indicator	MBD (%)	MAD (%)	RMSD (%)	MBD (%)	MAD (%)	RMSD (%)	MBD (%)	MAD (%)	RMSD (%)
Whole year	Horizontal(N = 7312)	-0.7	6.8	9.7	2.4	6.6	9.9	-4.4	7.3	9.8
	North (N = 7312)	-28.8	29.2	33.8	-18.5	18.9	24.5	-18.6	19.1	23.8
	South (N = 3345)	-5.2	15.0	18.5	1.2	11.0	15.9	-16.8	18.3	23.0
Summer	Horizontal (N = 2186)	5.1	8.7	10.8	7.7	9.6	13.9	-1.7	7.2	9.5
	North (N = 2186)	-26.9	27.4	29.5	-14.6	16.0	30.0	-18.0	18.1	22.7
	South (N = 1105)	2.2	14.6	17.2	11.0	13.8	20.0	-11.9	14.9	20.5
Winter	Horizontal (N = 1570)	-5.9	6.1	6.5	-5.9	6.0	6.6	-6.9	8.2	9.5
	North (N = 1570)	-31.4	31.4	31.8	-22.1	22.1	23.9	-21.4	21.4	23.8
	South (*) (N = 0)	-	-	-	-	-	-	-	-	-
Spring and fall	Horizontal (N = 3556)	-2.7	6.0	9.1	0.5	5.4	8.0	-5.6	7.2	9.9
	North (N = 3556)	-29.5	29.9	35.5	-19.7	19.8	25.7	-18.8	19.5	24.2
	South (N = 2240)	-8.7	15.7	19.4	-3.3	9.8	14.4	-19.8	20.5	24.5

especially in summer. As for the MBD, it can be seen that there is a turnaround from summer to winter, which may be due to the large difference of turbidity existing in Valencia during both seasons (as shown in Table 1). During the summer months the aerosol optical depth is maximum, increasing further the amount of diffuse radiation in the atmosphere, and therefore it is more difficult to model it. In this case most of the experimental values are below modeled values which results in the final set overestimating the measurements. In winter, the turbidity is lower and in most cases the process is reversed.

Finally, given the significance that the UVER acquires in the mid hours of the day (Martínez-Lozano et al., 2002), we have grouped the results provided by the model in three periods daily, around noon (10 h to 14 h UTC), and before (until 10 h) and after this time interval (after 14 h), all considering the seasonal division set out above. In view of the previous results, only the values obtained using AOD at 500 nm as an indicator of the load of aerosols have been considered for this analysis. Table 4 summarizes the results of the comparison with experimental values. The results show no new trend. They are acceptable, as in previous cases, on the horizontal plane, but on the north and south planes there are considerable mistakes, with RMSD of around 23% to 36% for the north plane and 14% to 25% for the south plane.

5 Conclusions

The SMARTS2 model is a model developed to determine spectral irradiance on a horizontal plane across the spectral range of solar radiation (280-4000 nm). It also applies to determine the spectral irradiance on vertical planes in that spectral range.

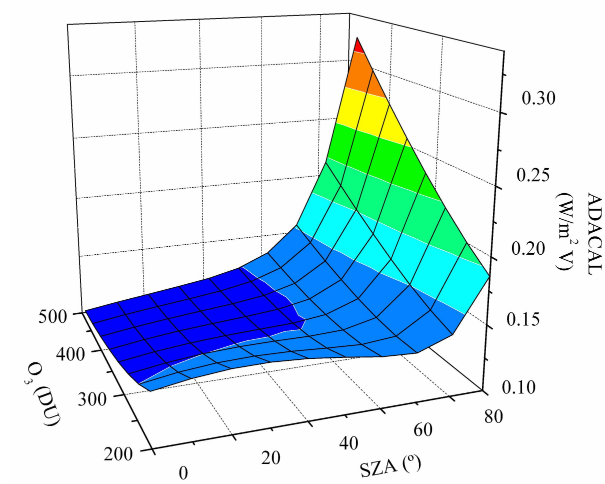

Figure 3. Calibration matrix for the UVB-1 radiometer. ADACAL is the calibration factor for each ozone value (O_3) and Solar Zenith Angle (SZA).

In this case, it has been used to determine UV erythemal radiation (UVER), both on horizontal and vertical planes oriented north and south. The results on a horizontal plane can be considered acceptable, obtaining in the comparison with the experimental values, relative RMSD values of 10.3%, when working with aerosol optical depth at 500 nm, and 15.8%, when working with Ångström β coefficient. As for the results obtained for the north and south planes, they reach very high deviations. The relative RMSD in these cases is 20.5% for the south plane and 32.5% for the north plane, in the best case there are aerosol optical depth values available to quantify the load of aerosols.

These mean deviations are much higher than those obtained when the model is applied to horizontal planes and in the range of visible radiation. In this case the RMSD values obtained are about 5% to 7% depending on the parameter used to quantify the aerosols (Utrillas et al., 1998).

The results obtained for the vertical planes do not improve by considering an annual trend, nor by taking into account the different seasons, nor by considering different periods throughout the day. We therefore consider that the SMART2 is not suitable for estimating UVER incidence on inclined planes. This could be explained on the basis that estimation of radiation on vertical planes supposes the estimation of the direct radiation and diffuse radiation, with the diffuse radiation reaching considerable significance in the UVB spectral range, of around 60% of the total radiation (Utrillas et al., 2007). The diffuse modeling on vertical planes in the UVB spectral range is a problem not yet solved, because the algorithms used for its calculation are the same as those used to calculate broadband radiation for the whole spectral range (Serrano et al., 2010).

Acknowledgements. This work has been funded by the Ministry of Science and Innovation (MICINN) through the projects CGL2007-60648 and CGL2009-07790 and by the Generalitat Valenciana through the project PROMETEO-2010-064. The collaboration of A. R. Esteve was made possible thanks to the grant BES-2006-12521.

References

Chandrasekhar, S., 1950: Radiative transfer, Oxford Univ. Press, UK. Republished by Dover, New York, USA (1960).

CIE, 2000: Erythema Reference Action Spectrum and Standard Erythema Dose, Commission Internationale de l'Éclairage Publications, Vienna, ISO 17166 CIE S 007 / E, CIE Standard., 4 pp.

Estellés, V., Martínez-Lozano, J. A., Utrillas, M. P., and Campanelli, M., 2007: *Columnar aerosol properties in Valencia (Spain) by ground-based Sun photometry*, J Geophys Res, **112**, doi: 10.1029/2006JD008 167.

Esteve, A. R., Marín, M. J., Martínez-Lozano, J. A., Tena, F., Utrillas, M. P., and Cañada, J., 2006: *UV index on tilted surfaces*, Photochem Photobiol, **82**, 1047–1052.

Frederick, J. E. and Lubin, D., 1988: *The budget of biologically active radiation in the earth atmosphere system*, J Geophys Res, **93**, 3825–3832.

Gueymard, C. A., 1995: Simple Model of the Atmospheric Radiative Transfer of Sunshine, version 2 (SMARTS2): Algorithms description and performance assessment, Report FSEC-PF-270-95, Florida Solar Energy Center.

Gueymard, C. A., 2005a: *Interdisciplinary applications of a versatile spectral solar irradiance model: A review*, Energy, **30**, 1551–1576.

Gueymard, C. A., 2005b: User's manual SMARTS, Solar consulting services, USA.

Holben, B., Eck, T., Slutsker, I., Tanré, D., Buis, J., Setzer, A., Vermote, E., Reagan, J., Kaufman, Y., Nakajima, T., Lavenu, F., Jankowiak, I., and Smirnov, A., 1998: *AERONET-a federate instrument network and data archive for aerosol characterization*, Rem Sens Environ, **66**, 1–16.

ICNIRP, 2004: *Guidelines on limits of exposure of UV radiation*, Health Phys, **87**, 171–186, International Commission on Non–Ionizing Radiation Protection.

Madronich, S., 1987: *Photodissociation in the atmosphere. Part 1. Actinic flux and the effect of ground reflections and clouds*, J Geophys Res, **92**, 9740–9752.

Martínez-Lozano, J. A., Marín, M. J., Tena, F., Utrillas, M. P., Sánchez-Muniosguren, L., González, C., Cuevas, E., Redondas, A., Lorente, J., de Cabo, X., Cachorro, V., Vergaz, R., de Frutos, A., Díaz, J. P., Expósito, F. J., de la Morena, B., and Vilaplana, J. M., 2002: *UV Index experimental values during the years 2000 and 2001 from the Spanish broadband UVB radiometric network*, Photochem Photobiol, **76**, 181–187.

McKinlay, A. F. and Diffey, B. L., 1987: *A reference spectrum for ultraviolet induced erythema in human skin*, CIE Journal, **6**, 17–22.

Meyer, B., Seckmeyer, G., and Kylling, A., 1997: *Systematic long-term comparison of spectral UV measurements and UVSPEC modelling results*, J Geophys Res, **102**, 8755–8766.

Parisi, A. V. and Kimlin, M. G., 1999: *Horizontal and sun-normal spectral biologically effective ultraviolet irradiances*, J Photochem Photobiol B-Biol, **53**, 70–74.

Pérez, R., Ineichen, P., Seals, R., and Zelenka, A., 1990: *Making full use of the clearness index for parametering hourly insolation conditions*, Sol Energy, **45**, 111–114.

Ricchiazzi, P., Yang, S., Gautier, C., and Sowle, D., 1998: *SBDART: A research and teaching software tool for plane-parallel radiative transfer in the Earth's atmosphere*, Bull Amer Meteorol Soc, **79**, 2101–2114.

Scotto, J., Cotton, G., Urbach, F., Berger, D., and Fears, T., 1988: *Biologically effective ultraviolet radiation: surface measurements in the United States. 1974 to 1985*, Science, **239**, 762–764.

Serrano, D., Marín, M. J., Utrillas, M. P., Tena, F., and Martínez-Lozano, J. A., 2010: *Measurement and modelling of global erythemal irradiance on inclined planes*, Tethys, **7**, 57–66, doi: 10.3369/tethys.2010.7.05.

Shettle, E. P. and Fenn, R. W., 1979: Models for the aerosol of the lower atmosphere and the effects of humidity variations on their optical properties, AFGL-TR-79-0214, Environmental Res. Paper no. 676, Hanscom AFL, MA.

Utrillas, M. P., Boscá, J. V., Martínez-Lozano, J. A., nada, J. C., Tena, F., and Pinazo, J. M., 1998: *A comparative study of SPECTRAL2 and SMARTS2 parameterised models based on spectral irradiance measurements at Valencia, Spain*, Solar Energy, **63**, 161–171.

Utrillas, M. P., Marín, M. J., Esteve, A. R., Tena, F., Cañada, J., and Martínez-Lozano, J. A., 2007: *Diffuse UVER radiation experimental values*, J Geophys Res, **112**, doi:10.1029/2007JD008 846.

Utrillas, M. P., Marín, M. J., Esteve, A. R., Estellés, V., Tena, F., Cañada, J., and Martínez-Lozano, J. A., 2009: *Diffuse ultraviolet erythematic irradiance (UVER) on inclined planes: a comparison of experimental and modelled data*, Photochem Photobiol, **20**, 1245–1253, doi: 10.1111/j.1751–1097.2009.00 573.x.

Utrillas, M. P., Martínez-Lozano, J. A., and Nuñez, M., 2010: *Ultraviolet radiation protection by a beach umbrella*, Photochem Photobiol, **86**, 449–456, doi: 10.1111/j.1751–

1097.2009.00 677.x.

Vilaplana, J. M., Cachorro, V. E., Sorribas, M., Luccini, E., de Frutos, A. M., Berjón, and de la Morena, B., 2006: *Modified calibration procedures for a Yankee Environmental System UVB-1 biometer based on spectral measurements with a Brewer spectrophotometer*, Photochem Photobiol, **82**, 508–514.

Webb, A., Weihs, P., and Blumthaler, M., 1999: *Spectral UV irradiance on vertical surfaces: A case study*, Photochem Photobiol, **69**, 464–470.

Weihs, P., 2002: *Influence of ground reflectivity and topography on erythemal UV radiation on inclined planes*, Int J Biometeorol, **46**, 95–104.

WMO, 1986: A preliminary Cloudless Standard for Radiation Computation, World Climate Programme, WCP-112. WMO/TD-No.24. WMO (World Meteorological Organization), Geneva, Switzerland.

WMO, 1998: Report of the WMO-WHO Meeting of Experts on Standardization of UV Indices and Their Dissemination to the Public, WMO Global Atmosphere Watch No. 127, WMO/TD No. 921. WMO (World Meteorological Organization), Geneva.