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A SIMPLE ALGORITHM FOR THE COMPUTATION OF THE SPECTRAL DISTRIBUTION OF THE SOLAR IRRADIANCE AT SURFACE

Lucien Wald
MINES ParisTech, PSL Research University
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Centre Observation, Impacts, Energie (O.I.E.)
MINES ParisTech / ARMINES
Rue Claude Daunesse – CS 10207 - F-06904 SOPHIA ANTIPOLIS CEDEX
Tél. : +33 (0)4.93.95.75.75 • Fax : +33 (0)4.93.67.89.08
http://www.oie.mines-paristech.fr/

ABSTRACT

The downwelling solar irradiance received at ground level has many effects on many aspects, from climate to biomass or human health. There is a need for an accurate knowledge of the spectral distribution of the solar irradiance anytime anywhere. This simple algorithm has been developed that estimates the spectral distribution of the solar irradiance at surface from the sole knowledge of the total solar irradiance at surface and the top of the atmosphere. The spectral distribution ranges from 280 nm to 1000 nm. The report also documents the published validations that have been made against ground measurements and other sources in UV. The report provides a partial list of articles making use of this algorithm in several domains related to the human health. Though most of the publications deal with UV radiation, the algorithm can be applied to any spectral interval.

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1 INTRODUCTION AND GOALS OF THE DOCUMENT

1.1 The downwelling solar irradiance at surface

The downwelling solar irradiance received at ground level has many effects on many aspects, from climate to biomass. For example, it is known for having an influence on human health; see a review of the beneficial and adverse effects in Juzeniene et al.[1].

The solar irradiance at the top of atmosphere exhibits a spectral distribution which, to a first approximation, may be considered as constant. This is not the case at ground level because of the many interactions of the downwelling radiation with the atmospheric constituents, including clouds. The radiation may be absorbed by gases and by aerosols at specific wavelengths or spectral ranges, and the intensity of the scattering by molecules, cloud droplets and ice crystals and aerosols depends on the wavelength of the radiation. It follows that the spectral distribution of the downwelling solar irradiance at surface depends in time and space.

The solar irradiance integrated over the whole spectrum is called total solar irradiance at the top of the atmosphere or at ground level, depending on the case.

1.2 Needs for the spectral distribution of the irradiance

There is a need to know the downwelling solar irradiance in certain spectral ranges in several domains. For example, epidemiologists may need estimates of in the UV-A range; agronomists may need estimates of the photosynthetically active radiation (PAR); architects need estimates of the daylight in buildings etc.

At several occasions, the effect of the downwelling solar irradiance on an object is characterized by a typical spectral response, also known as action spectrum in human health. The most likely known of these action spectra is the standardized action spectrum for erythema, also known as the CIE (Commission Internationale de l'Eclairage) spectrum; there are also other action spectra related to skin cancer and melanoma. The spectral response in PAR depends on the plant. In solar energy, the spectral response of the PV cell will characterize the capability of the PV panel to produce electricity in given conditions and given PV technology.

The only way to take into account a known spectral response or action spectrum is to multiply a detailed spectral distribution of the irradiance, say every 1 nm or 10 nm, by this response. This remark demonstrates the need for an accurate knowledge of the spectral distribution of the downwelling solar irradiance any time anywhere.

[1] Juzeniene, A.; Brekke, P.; Dahlback, A.; Andersson-Engels, S.; Reichrath, J.; Moan, K.; Holick, M.F.; Grant, W.B.; Moan, J. Solar radiation and human health. Rep. Prog. Phys., 74, 066701, doi: 10.1088/0034-4885/74/6/066701, 2011.

1.3 Goals of the document

This knowledge is hardly available though several databases covering the world are emerging. More complete is the knowledge of the total solar irradiance at surface. Satellite data play a key role in supporting the creation of this knowledge.

Several algorithms have been developed that estimate the spectral distribution of the solar irradiance at surface from the total solar irradiance at surface and other detailed meteorological data.

The algorithm presented in this document estimates the spectral distribution of the solar irradiance at surface from the sole knowledge of the total solar irradiance at surface and at the top of the atmosphere. It is derived from an original one set up by the Belgium meteorological office in the 1990's. The spectral distribution ranges from 280 nm to 1000 nm.

The report also documents the published validations that have been made against ground measurements and other sources in UV. Eventually, the report provides a partial list of articles making use of this algorithm in several domains related to the human health.

2 THE EMPIRICAL ALGORITHM FROM THE EUROPEAN SOLAR RADIATION ATLAS

Crommelynck and Joukoff exploited spectral measurements performed at Uccle, in Belgium, to develop a simple algorithm for the estimation of the spectral distribution of the solar irradiance at ground level from measurements of the total irradiance and the sunshine duration[2, 3]. This algorithm has been detailed in the European Solar Radiation Atlas[4, 5] (ESRA) and is detailed hereafter.

Let

- λ be the wavelength expressed in nm;
- *I* be the total irradiance at the ground level;
- $I(\lambda)$ be the irradiance at surface at λ; it has the same unit than *I*.

In the ESRA algorithm, the spectral distribution covers the range [310, 1000] nm, with a sampling of 10 nm in width. The spectral distribution is approximated by a triangular shape centered at 465 nm:

$$I(\lambda) = 1.163\ 10^{-5}\ (\lambda - 300)\, f(\lambda)\, I,\ 300\,\text{nm} < \lambda \leq 465\,\text{nm} \tag{1}$$

$$I(\lambda) = (3.1515\ 10^{-3} - 2.6510\ 10^{-6}\ \lambda)\, f(\lambda)\,)\, I,\ 450\,\text{nm} < \lambda \leq 900\,\text{nm} \tag{2}$$

where $f(\lambda)$ is a spectral factor and λ is expressed in nm.

Two sets of spectral factors $f(\lambda)$ are proposed in tabular form in ESRA (pages 158-159): one for cloud-free skies $fc(\lambda)$, and the other for overcast skies $fb(\lambda)$ and are reported hereafter. The spectral factor $f(\lambda)$ for any sky condition is obtained by linear interpolation between the clear and overcast conditions, where the sky condition is characterized by the relative sunshine duration *S/S0*, where *S* is the sunshine duration during the day and *S0* the astronomical daytime:

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[2] Crommelynck, D., and A. Joukoff. A simple algorithm for the estimation of the spectral radiation distribution on a horizontal surface, based on global radiation measurements. Solar Energy 45, 131-137, doi:10.1016/0038-092X(90)90047-G, 1990.

[3] Joukoff, A., and D. Crommelynck. Estimation of the spectral radiation distribution using a simple algorithm. In Proceedings of the Int. Radiation Symposium, Tallin, Estonia, 3-8 August 1922, pp. 241-244. Keevallik S. and Karner O. (Eds), Deepak Publishing, 1993.

[4] Greif, J. J., Scharmer, K., Aguiar, R., Albuisson, M., Beyer, H.-G., Borisenkov, E. P., Bourges, B., Czeplak, G., Lund, H., Joukoff, A., Page, J. K., Terzenbach, U. and Wald, L.: The European Solar Radiation Atlas : Database, Models and Exploitation Software, Vol 2, Presse des Mines, Paris, France, 290 p., 2000.

[5] Page, J., Albuisson, M., and Wald, L.: The European solar radiation atlas: a valuable digital tool. Solar Energy, 71, 81-83, doi:10.1016/S0038-092X(00)00157-2, 2001. Page, J., Albuisson, M., and Wald, L.: The European solar radiation atlas: a valuable digital tool. Solar Energy, 71, 81-83, doi:10.1016/S0038-092X(00)00157-2, 2001.

$$f(\lambda) = [1 - fc(\lambda)]\ S/S0 + [1 - fb(\lambda)]\ (1 - S/S0) \qquad (3)$$

The spectral factors $fc(\lambda)$ and $fb(\lambda)$ are given in the following tables.

λ	$fc(\lambda)$	$fb(\lambda)$
310	0.299131	0.052609
320	-0.072117	-0.436417
330	-0.470114	-1.083667
340	-0.163680	-0.507508
350	-0.045845	-0.320075
360	0.104993	-0.135391
370	0.094821	-0.128547
380	0.193805	-0.002148
390	0.227752	0.092124
400	-0.028009	-0.137366
410	-0.038280	-0.170108
420	0.032069	-0.072013
430	0.187228	0.127635
440	0.088508	0.028846
450	0.001133	-0.071541
460	0.051250	0.008413
470	0.095797	0.048258
480	0.040447	-0.01389
490	0.067742	0.026979
500	0.070530	0.049169
510	0.049300	0.027436
520	0.085463	0.07242
530	0.032227	0.007355

λ	$fc(\lambda)$	$fb(\lambda)$
540	0.037216	0.026798
550	0.019879	0.000174
560	0.036850	0.033850
570	0.026988	0.048032
580	0.005614	0.025231
590	0.041526	0.100624
600	-0.013070	0.001933
610	-0.004661	0.018790
620	-0.006657	0.012116
630	0.015066	0.055732
640	-0.015301	0.022291
650	-0.000992	0.062014
660	-0.029207	0.011542
670	-0.055281	-0.016555
680	-0.060831	-0.011822
690	0.058582	0.124584
700	-0.023561	0.066365
710	-0.073968	-0.036060
720	0.096588	0.240797
730	0.036455	0.151632
740	-0.071741	-0.110799
750	-0.104140	-0.196811
760	0.423049	0.294647

λ	$fc(\lambda)$	$fb(\lambda)$
770	-0.061262	-0.137052
780	-0.137308	-0.235992
790	-0.110311	-0.147491
800	-0.101120	-0.144815
810	-0.084861	-0.114738
820	0.052705	0.122264
830	-0.007400	0.037108
840	-0.112113	-0.176035
850	-0.083078	-0.171275
860	-0.132166	-0.235954
870	-0.136049	-0.256693
880	-0.138935	-0.241424
890	-0.139798	-0.235224
900	0.115449	0.238556
910	0.111406	0.248487
920	0.000457	0.106361
930	0.341127	0.553565
940	0.438448	0.689698
950	0.425510	0.666235
960	0.285605	0.540856
970	-0.070392	0.057491
980	-0.214837	-0.061214
990	-0.443858	-0.451716
1000	-0.470468	-0.524536

These formulae stand for irradiance as well as for irradiation without any change. It stands also for any unit of irradiance or irradiation as in these formulae, $I(\lambda)$ has the same unit than I.

$I(\lambda)$ is the irradiance for a specific wavelength. For a given spectral range, it must be integrated over the range, i.e. one must sum up the various $I(\lambda)$ to obtain I_{range}. Because the spectral width of $f(\lambda)$ is 10 nm, the irradiance for a given range is I_{range} multiplied by 10. This holds for a range of 10 nm, for example the irradiance for the range [305, 315] nm is equal to 10 times $I(\lambda=310)$.

3 OUR ALGORITHM: AN ADAPTATION OF THE ESRA ONE

The ESRA algorithm has been revised in two aspects, because it does not allow the computation of the irradiance in the UV-B range, and because the sunshine duration is known in a limited number of sites.

The ESRA algorithm does not provide spectral factors below 310 nm, i.e. for the UV-B range. We palliate this lack by assuming that the irradiance I_{UVB} can be computed from the spectral irradiance *I(310)* at 310 nm by using the ratio of these same quantities but outside the atmosphere, which is approximately 1.8:

$$I_{UVB} = 1.8\ 10\ I(\lambda=310) \quad (4)$$

As written above, the sunshine duration is known in a limited number of sites. As the total solar irradiance at the top-of-atmosphere *I0* is easy to compute, we propose a modification of the algorithm to substitute the sunshine duration by the clearness index *KT*, defined as the ratio *I/I0*. The clearness index may be computed from irradiance or irradiation since it is a ratio.

The Angström-Prescott relationship enables such a substitution:

$$KT = a + b\ S/S0 \quad (5)$$

where *(a, b)* are site-specific parameters. Though this relationship has been established for monthly values, we assume that it holds for shorter durations such as a day.

Finally, we neglect the variation of the parameters *(a, b)* in space. Therefore, we can state that

- for overcast sky: $S/S0 = 0$, i.e., $KT = KTmin = a$,
- and for clear-sky: $S/S0 = 1$, i.e., $KT = KTmax = a+b$.

From ESRA, one may set *KTmin* and *KTmax* to 0.1 and 0.7 for Europe, from which parameters *a* and *b* can be computed.

KT must be constrained in the interval [0.1, 0.7]:

$$KT^* = max(0.1, min(KT, 0.7)) \quad (6)$$

it comes:

$$f(\lambda) = (1 - fb(\lambda)) + (fb(\lambda) - fc(\lambda))\ [(KT^* - KTmin)/(KTmax - KTmin)] \quad (7)$$

or

$$f(\lambda) = 1 - 0.833\, fb(\lambda) - 0.167\, fc(\lambda) + 1.667\, (fb(\lambda) - fc(\lambda))\, KT^* \quad (8)$$

This model is an affine relationship between $(I(\lambda) / I)$ and KT.

4 VALIDATION FOR UV - EXAMPLES OF USE

Our algorithm has not been extensively compared to other models or in situ measurements for spectral bands, except UV. One of the difficulties in validation is that the outcomes depend on the accuracy of the total global solar irradiance input to our algorithm. If this input is inaccurate, the algorithm outputs will be inaccurate, too.

In the case of UV, our algorithm yields the following formulae:

UV-B, $I_{UVB} = [1.897 - 0.860\ KT^*]\ 10^{-3}\ I$ (9)

UV-A, $I_{UVA} = (7.210 - 2.365\ KT^*)\ 10^{-2}\ I$ (10)

where $KT^* = max(0.1, min(KT, 0.7))$,

and I is the total irradiance, I_{UV} is the unknown irradiance in UV-B or UV-A, and KT is the clearness index. In these formulae, I_{UV} has the same unit than I. These formulae stand also for irradiation.

4.1 Early comparison against personal dosimeters (2006)

Daily doses, i.e. daily irradiation in UV, predicted by our algorithm with the total irradiation from the HelioClim-1 database as input, were compared to measurements of UV-A and UV-B exposure of children recorded with personal dosimeters with assessment through a detailed questionnaire. A large correlation was found between predicted values and dosimeter readings when the latter are corrected for type of use, exposure in the shade, and environment. It was concluded that compared to dosimeters, this combination of HelioClim-1 and our algorithm give a good estimate of individual UV-A and UV-B exposure, independently of exposure conditions and could be used to estimate actual exposure.

Boniol, M., M.S. Cattaruzza, L. Wald, M.-C. Chignol, M.A. Richard, M.T. Leccia, F. Truchetet, C. Renoirte, P. Vereecken, P. Autier and J.-F. Dore (2006) Individual sun exposure can be assessed using meteorological satellite measurements. In Epidemiology – International Conference Epidemiology and Exposure, 2-6 September 2006, Paris, France.

4.2 Comparison against ground measurements made every 15 min (2010)

Though the Wald algorithm applies best to daily or monthly values, irradiation or irradiance, Wald et al. (2010) performed comparisons between the results of the Wald algorithm and coincident ground measurements made every 15 min in two sites in Europe: Lille in Northern France, and El Arenosillo in Southern Spain. Inputs to our algorithm were the total 15 min irradiations from the satellite-derived database HelioClim-3v2.

The data were spanning over two years: 2005-2006. It was found that *i)* the form of the model is correct, and *ii)* there is no noticeable influence of the solar zenithal angle or year on the performances of the model. For both sites, I_{UVB} is underestimated by 20% to 30%, and I_{UVA} is overestimated by the same relative amount.

The large correlation, greater than 0.93, between measurements and predicted values indicate a linear relationship between them. This means that the changes in space and time in UV are well reproduced by the predicted values though the changes are dampened in the case of UV-B and amplified in UV-A.

> Wald, L., A. Arola, C. Brogniez and J.M. Villaplana (2010) A preliminary assessment of the quality of UV data derived from the database HelioClim-3. 10th EMS Annual Meeting (European Meteorological Society), Bern, Swizerland, 13-17 September 2010.

4.3 Comparison against daily irradiation in UV-A measured at several ground stations in Europe (2016)

Aculinin et al. (2016) have validated the algorithm, called the Wald algorithm in their paper, against measurements of daily irradiation in UV-A [315, 400] nm made at several stations located in mid-latitude Europe, mostly in Belgium. They use three different databases derived from satellite images: HelioClim-3 (versions 4 and 5) and CAMS Radiation Service (CRSv2) derived from Meteosat images. These databases have been accessed through the SoDa Service[6] (www.soda-pro.com).

It was found that acceptable results are attained with the Wald algorithm (2012). The relative RMSE is in the range 10%–20% of the mean of the measurements for HelioClim-3 v4 or v5 and is slightly more for CRSv2, between 10% and 30%. The correlation coefficients are large and most of the variability contained in the UV measurements is captured by the algorithm, thus demonstrating that the Wald algorithm can be used in studies where correlation plays a major role.

> Aculinin, A., Brogniez, C., Bengulescu, M., Gillotay, D., Auriol, F., Wald, L.: Assessment of several empirical relationships for deriving daily means of UV–A irradiance from Meteosat–based estimates of the total irradiance. Remote Sensing, 8(7), 537; doi:10.3390/rs8070537, 2016.

[6] Gschwind, B., Ménard, L., Albuisson, M., and Wald, L.: Converting a successful research project into a sustainable service: the case of the SoDa Web service. Environmental Modelling and Software, 21, 1555-1561, doi:10.1016/j.envsoft.2006.05.002, 2006.

4.4 Comparisons of UV maps (2016)

Our algorithm was used in the framework of the EU-funded Eurosun project (2007–2011)[7] whose main objective was to monitor ultraviolet exposure across Europe and its effects on incidence of skin cancers and cataracts in support to the different volumes of the publication “Cancer Incidence in Five Continents” of the World Health Organization[8].

It has been applied to the HelioClim databases: HelioClim-1[9, 10] and HelioClim-3[11] that contain daily total irradiation for Europe since 1985. This yields the Eurosun database covering the period 1988-2007 for supporting analyses of effects on incidence of skin cancers through maps and exposure of individuals. Maps of 5-years average of monthly means of UV daily doses were made and compared to other maps of lower spatial resolution from the COST no726 project[12] and from KNMI/ESA[13]. The coincidences of features between these maps and the Eurosun ones support the validity of the Eurosun database in terms of spatial and temporal variability, and hence of our algorithm[14].

[7] Eurosun. Measuring the Exposure of Individuals and Populations in Europe to UV Radiation by Using the Data of Meteorological Satellites. Available online: http://www.eurosun-project.org (accessed on 8 December 2015).
[8] CI5: Cancer Incidence in Five Continents. Available online: http://ci5.iarc.fr (accessed on 8 December 2015).
[9] Lefèvre, M., Diabaté, L., and Wald, L.: Using reduced data sets ISCCP-B2 from the Meteosat satellites to assess surface solar irradiance. Solar Energy, 81, 240-253, doi:10.1016/j.solener.2006.03.008, 2007.
[10] Lefèvre, M., Blanc, P., Espinar, B., Gschwind, B., Ménard, L., Ranchin, T., Wald, L., Saboret, L., Thomas, C., and Wey, E.: The HelioClim-1 database of daily solar radiation at Earth surface: an example of the benefits of GEOSS Data-CORE. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 7, 1745-1753, doi:10.1109/JSTARS.2013.2283791, 2014.
[11] Blanc, P., Gschwind, B., Lefèvre, M., and Wald, L.: The HelioClim project: Surface solar irradiance data for climate applications. Remote Sensing, 3, 343-361, doi:10.3390/rs3020343, 2011.
[12] COST No 726 at www-med-physik.vu-wien.ac.at/uv/cost726/cost726.htm
[13] Tropospheric Emission Monitoring Internet Service at www.temis.nl
[14] Wald, L. Elements on the computation of UV maps in the Eurosun database. Internal Report. 2012. Available online: http://hal-mines-paristech.archives-ouvertes.fr/hal-00788420/document.

5 EXAMPLES OF USE

Several usages of the presented algorithm are known to the author. Others may exist. Hereafter is a non-exhaustive list of publications where our algorithm has been exploited.

5.1 UV-related studies on cancer

1. Coste, A.; Goujon, S.; Boniol, M.; Marquant, F.; Faure, L.; Doré, J.-F.; Hémon, D.; Clavel, J. Residential exposure to solar ultraviolet radiation and incidence of childhood hematological malignancies in France. Cancer Causes Control, 26, 1339–1349, doi: 10.1007/s10552-015-0629-x, 2015.

2. Fortes, C.; Mastroeni, S.; Bonamigo, R.; Mannooranparampil, T.; Marino, C.; Michelozzi, P.; Passarelli, F.; Boniol, M. Can ultraviolet radiation act as a survival enhancer for cutaneous melanoma? Eur. J. Cancer Prev., 25, 34–40, doi: 10.1097/CEJ.0000000000000127, 2016.

3. Coste A, Hémon D, Orsi L, Boniol M, Doré JF, Faure L, Clavel J, Goujon S. Residential exposure to ultraviolet light and risk of precursor B-cell acute lymphoblastic leukemia: assessing the role of individual risk factors, the ESCALE and ESTELLE studies. Cancer Causes Control, 28, 1075-1083, doi: 10.1007/s10552-017-0936-5, 2017.

5.2 UV-related studies on eye disease

1. Delcourt, C.; Cougnard-Grégoire, A.; Boniol, M.; Carrière, I.; Doré, J.-F.; Delyfer, M.-N.; Rougier, M.-B.; Le Goff, M.; Dartigues, J.-F.; Barberger-Gateau, P.; Korobelnik, JF. Lifetime exposure to ambient ultraviolet radiation and the risk for cataract extraction and age-related macular degeneration: the Alienor study. Investig. Ophthalmol. Vis. Sci., 55, 7619–7627, doi: 10.1167/iovs.14-14471, 2014.

2. Schweitzer C, Korobelnik JF, Boniol M, Cougnard-Gregoire A, Le Goff M, Malet F, Rougier MB, Delyfer MN, Dartigues JF, Delcourt C. Associations of biomechanical properties of the cornea with environmental and metabolic factors in an elderly population: the ALIENOR study. Investig. Ophthalmol. Vis. Sci., 57, 2003–2011, doi: 10.1167/iovs.16-19226, 2016.

5.3 UV-related studies on Parkinson disease

1. Kravietz Adam, Ka Sofiane, Wald Lucien, Dugravot Aline, Singh-Manoux Archana, Moisan Frédéric, Elbaz Alexis, Association of UV radiation with Parkinson disease incidence: a nationwide French ecologic study. Environmental Research, 154, 50-56, doi: 10.1016/j.envres.2016.12.008, 2017.