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SOLAR SPECTRAL IRRADIANCE

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II

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SOLAR SPECTRAL IRRADIANCE

SUMMARY

CIE TC2-17 was formed with the purpose of updating CIE Publication No.20 (TC-2.2) "Recommendations for the integrated irradiance and the spectral distribution of simulated solar radiation for testing purposes". The present document is the first of two, of which the second will deal with solar simulators. It gives a brief overview of parameterization methods and contains a number of tables and figures for solar spectral irradiances for typical atmosphere conditions defined by a set of meteorological parameters. The calculated data show satisfactory agreement with results obtained by direct measurement.

DISTRIBUTION SPECTRALE DE L'ÉCLAIREMENT SOLAIRE

RÉSUMÉ

Le but de Comité Technique CIE TC2-17 était de mettre à jour la publication CIE n° 20 (TC2.2): "Recommendations concernant l'éclairage énergétique et la répartition spectrale du rayonnement solaire en vue de sa reproduction artificielle pour des essais". Le présent document est la première de 2 parties (la deuxième partie traitera des simulateurs solaires). Ce premier document décrit brièvement les méthodes de paramétrisation et présente des tables de données relatives à l'éclairage énergétique spectral du rayonnement solaire pour certains types de conditions atmosphériques définies par un ensemble de paramètres météorologiques. L'accord entre les valeurs calculées et les valeurs mesurées est satisfaisant.

SOLARE SPEKTRALE BESTRAHLUNGSSTÄRKE

ZUSAMMENFASSUNG

Die CIE TC2-17 hat die Aufgabe die Publikation CIE No.20 CIE2.2 "Empfehlung über die Gesamtbestrahlungsstärke und die spektrale Verteilung künstlicher Sonnenstrahlung für Prüfzwecke" auf den neuesten Stand zu bringen. Die vorliegende Publikation ist der erste Teil von zwei Teilen, von denen der zweite Solarsimulatoren behandeln wird. Der erste Teil, der hier vorliegt, gibt einen kurzen Überblick der Methoden der Parametrisierung und enthält Tabellen und Abbildungen für solare spektrale Bestrahlungsstärkeverteilungen für typische Zustände der Atmosphäre, die durch eine Gruppe meteorologischer Parameter definiert sind. Die berechneten Werte stimmen zufriedenstellend mit den Ergebnissen direkter Messungen überein.

1. INTRODUCTION

It was decided to revise and update CIE Publication No.20 (TC-2.2) 1972. The main reasons for this decision could be summarized as follows.

It has become obvious that the solar spectral irradiance data on which the recommendations in the original document were based were no longer the most reliable. During the past decade a vast amount of new data has become available both through modernized measurement techniques as well as improved modelling and parameterization methods. Contrary to the situation some years ago, the stage has now been reached where results for solar spectral irradiances at ground level as measured and those obtained by reliable modeling, using extraterrestrial data as basis, show agreement to accuracies well within predictable or estimable uncertainties. It has thus become possible to calculate solar spectral irradiance levels and characteristics for any site on earth provided appropriate meteorological and atmospheric parameters are applied in reliable modeling formulas. This enables close simulation of solar irradiance characteristics for any geographical site, without the need of having to make in situ measurements.

It is also desirable that the number of spectral bands for which integrated solar irradiance levels are given, should be increased, especially in the ultraviolet region where the degradation coefficient for organic material increases nearly exponentially with a decrease in wavelength.

The aim of the report is to present data and recommend methods for calculating the integrated and spectral irradiance of the extraterrestrial and ground level solar radiation as a basis for simulation for testing purposes.

These data are required in

- * aerospace technique for testing satellites and space vehicles in sun simulators,
- * space biology for testing biological objects under extra-terrestrial conditions in laboratory,

- * technology for the purpose of testing the resistance of technical objects to irradiance in laboratories,
- * biology and medical science for irradiation of organisms in solaria under the condition found in nature.
- * photovoltaic conversion for precise calculation of efficiencies and testing in solar simulators.

The determination of the integrated irradiance of the extraterrestrial solar radiation, which was called "Solar Constant" after Pouillet as early as 1838, was originally based upon extrapolation of measured results at ground level. These were later followed by measurements from high mountain sites, balloons, aircraft and spacecraft.

For obtaining ground level spectral irradiance data, use has been made of modelling, using extraterrestrial data as a basis and taking into account atmospheric attenuation parameters. This has been supplemented by direct spectral measurements.

The following recommendations are based upon extraterrestrial data of the World Meteorological Organization (WMO), which was mainly derived from the data of Labs and Neckel, and of modeled data for atmospheric conditions based on the parameterization method according to Justus and Paris.

2. EXTRATERRESTRIAL SOLAR RADIATION

2.1 Extraterrestrial solar irradiance

From the sun, the planet Earth receives electromagnetic as well as corpuscular radiation. The electromagnetic radiation of the sun is called solar radiation. The solar radiation incident on the upper boundary of the terrestrial atmosphere is called extraterrestrial solar radiation.

Since the earth moves around the sun in an elliptical orbit, the ecliptic, during one year, the distance from the sun to the earth and hence the irradiance of extraterrestrial solar radiation varies with time of the year. The actual value E_{0J} of extraterrestrial solar irradiance on Julian day J , ($J = 1, \dots, 365$) is given by

$$E_{0J} = E_0 \cdot (R/R_J)^2 \quad (1)$$

where R_J = actual earth-sun distance on day J

R = mean earth-sun distance

= 1 astronomical unit (AU)

= $150 \cdot 10^6$ km,

E_0 = extraterrestrial solar irradiance

at mean earth-sun distance

= solar constant (see below).

The "squared distance reduction" $(R/R_J)^2$ is found in astronomical tables or may be calculated with sufficient accuracy with the help of

$$(R/R_J)^2 = 1 + 2e \cdot \cos [\omega(J-1) - \psi] \quad (2)$$

where $2e$ = 0,0334 = twice the numerical eccentricity of the ecliptic,

ω = $360^\circ/365,25$ per day = $0,9856^\circ$ per day

= mean angular velocity of the revolution of the earth around the sun,

J = number of Julian day, counted from 1 = 1 Jan, 1200 true solar time (TST),

ψ = $1,735^\circ$ = difference of the geocentric longitudes of the sun at perigee and at 1 Jan, 1200 TST, respectively.

Numerically, Eq. (2) reads

$$(R/R_J)^2 = 1 + 0,0334 \cdot \cos (0,9856^\circ \cdot J - 2,7206^\circ). \quad (3)$$

The "squared distance reduction" varies from 1,0334 at perigee (on 3 January) to 0,9666 at apogee (on 3 July) that is by about $\pm 3.3\%$ during the year.

2.2 The solar constant

As mentioned, the extraterrestrial solar irradiance at mean earth-sun distance is called the solar constant. Direct measurements of the solar constant were taken by instruments aboard high-altitude air-

craft, balloons, rockets and satellites in 1967-1969 and, with appreciably improved accuracy, since 1976. For critical summaries, see Fröhlich and Brusa [1] and Fröhlich [2], for instance.

As a result of these re-determinations of the solar constant, the Commission for Instruments and Methods of Observation of the World Meteorological Organization (WMO-CIMO) [3] agreed to adopt for meteorological purposes a value of the solar constant of

$$E_0 = (1,367 \pm 0,007) \text{ kW} \cdot \text{m}^{-2}. \quad (4)$$

Any short term fluctuations of the solar constant are confined to the uncertainty limits given, i.e. to $\pm 0,5\%$. On the other hand, short or even longer term variations of the solar constant cannot be excluded on the basis of the present state of knowledge.

2.3 Spectral distribution

When the spectral distribution of extraterrestrial solar radiation is considered, the spectral irradiance reduced to mean earth-sun distance is usually meant. Thus, the integral over wavelength of the spectral extraterrestrial solar irradiance, $E_{0\lambda}$, yields the solar constant:

$$\int_{\lambda=0}^{\infty} E_{0\lambda} \cdot d\lambda = E_0. \quad (5)$$

The 1967-1969 measurements already mentioned were processed by Thekaekara [4, 5, 6, 7] to a recommendation for the extraterrestrial solar spectrum which yielded the value $1,353 \text{ kW} \cdot \text{m}^{-2}$ for the solar constant. However, calibration and operational behaviour of the measuring instruments used were not completely above criticism so that besides Thekaekara's values, the results obtained by Labs and Neckel [8, 9] from careful measurements at an 3600 m altitude observatory of the radiance of the sun's center were also used. Since the differences in the ultraviolet and infrared spectral ranges of the two spectral distributions approximately compensate each other, the value $1,358 \text{ kW} \cdot \text{m}^{-2}$ derived from Labs and Neckel for the solar constant came out very close to Thekaekara's value.

In order to obtain the mean radiance of the total solar disk from the radiance of the sun's center, the so-called limb-darkening which stems from the radial stratification of the sun, is to be considered. After new improved observations of the limb-darkening had become available, Neckel and Labs [10] have revised their measurements mentioned above and presented an improved solar spectrum, the mean errors of which were estimated as smaller than 1% in the visible and infrared spectral regions, and smaller than 1,5% in the ultraviolet spectral region. For the resulting solar constant the authors stated the range of uncertainty from 1,368 to 1,377 kW·m⁻².

On the basis of the values of Neckel and Labs [10], WMO-CIMO [3], for meteorological purposes adopted an extraterrestrial solar spectrum which has been adapted in the ultraviolet region to data of Arvesen et.al. [11] and of Heath and Thekaekara [12], and in the infrared region to data of Smith and Gottlieb [13]. Furthermore, the whole spectrum had been raised by 0,14% to make its integral equal to the recommended value 1,367 kW·m⁻² of the solar constant derived from independent measurements, (see Eq. 4).

The spectral distribution of extraterrestrial solar radiation adopted by WMO has become known as WMO spectrum. Dehne and Kasten [14] have processed the data published by WMO to a more practicable form (see Appendix 4.1, Table 1). The first column indicates the wavelength intervals $\Delta\lambda$, the widths of which are

- 2 nm from 250 to 800 nm,
- 5 nm from 800 to 2000 nm,
- 20 nm from 2000 to 4000 nm.

The second column contains the fractional irradiances $\Delta E_0(\lambda)$, in W·m⁻², within each interval; the third column represents the corresponding mean spectral irradiances $E_{0\lambda} = \Delta E_0(\lambda)/\Delta\lambda$, in W·m⁻²·nm⁻¹. The $E_0(\lambda)$ given in Table 1 may also be found in Iqbal [15]. Figure 1 a and b (Appendix 4.2) show graphical representations of the spectral irradiance of extraterrestrial solar radiation.

More recently, Neckel and Labs [16] have again improved their spectral data based on their own new measurements of the limb-darkening of the sun. The standard deviations of the 1984 spectral values have been reduced to 0,2%; the maximum statistical error to 0,5%. However, since there are not any significant systematic differences between the 1984 and 1981 values, the so-called WMO spectrum which is based on the 1981 values is recommended to be maintained as the standard extra-terrestrial solar spectrum for meteorological and technical purposes.

3. SOLAR RADIATION AT THE EARTH SURFACE

3.1 Direct, diffuse and global solar radiation

On its path through the atmosphere, solar radiation is attenuated by scattering and absorption by the molecules of the air, by aerosol particles suspended in the air and by water droplets and ice crystals. That part of the extraterrestrial solar radiation which reaches the earth surface is called direct solar radiation. Direct solar radiation received on a plane being normal (perpendicular) to the solar beam is called direct normal solar radiation I , the irradiance E_I . If γ = elevation angle and ζ = zenith angle of the sun, then $E_I \cdot \sin \gamma = E_I \cdot \cos \zeta$ is the direct solar radiation on a horizontal plane.

Part of the solar radiation scattered in the atmosphere reaches the earth surface as so-called diffuse solar radiation D ; the irradiance on a horizontal plane is E_D . The sum of direct and diffuse solar radiation on a horizontal plane at the earth surface is called global solar radiation G . The irradiance is

$$E_G = E_I \cdot \gamma \sin + E_D = E_I \cdot \cos \zeta + E_D. \quad (6)$$

The term E_D includes solar radiation which is scattered back and forth by the earth's surface and the atmosphere.

When two of the quantities E_G , E_I , E_D are given, the third can be determined. In meteorological radiation networks, E_G and usually E_D are recorded. For model calculations E_I and E_D are computed.

3.2 Spectral irradiances based on rigorous radiative transfer models

Based on the fundamental work on radiative transfer by Chandrasekhar [17], Sekera and collaborators [18, 19] computed the spectral global solar irradiance including all orders of multiple scattering in a dry dust-free atmosphere and taking reflection by the earth surface and absorption by the atmospheric ozone layer into account. Dave and collaborators [20, 21, 22, 23] extended these investigations to realistic atmospheres with given vertical profiles of aerosol and gas concentrations. The results of these workers are frequently used as standard values for comparison with parameterized models (see below).

In recent years, Bird and collaborators [24, 25, 26] have presented radiation models with refined spectral resolution, making use of spectral data of the atmosphere compiled in [27, 28, 29, 30]. The latest version of Bird's model [26] contains several important improvements, particularly the use of the WMO-spectrum [3] for the extra-terrestrial spectral solar irradiance. On the basis of [26], Bird and Hulstrom [31] computed spectral distributions of direct normal solar radiation and global solar radiation on a plane normal to the solar beam. For standardization purposes, the spectral distributions given for vertical incidence ($\zeta = 0^\circ$, $\gamma = 90^\circ$) are recommended to give global solar radiation on a horizontal plane.

Table 2, second column gives the spectral irradiances of direct normal solar radiation, $E_{I\lambda}$, for $\zeta = 0$ at sea level (so that the relative air mass is 1), water vapour content 1,42 cm precipitable water (PW), ozone content 0,34 cm at standard temperature and pressure (STP), albedo surface reflection of the earth surface 0,2 and turbidity (expressed as spectral optical depth of aerosol extinction at $\lambda = 0,5 \mu\text{m}$) 0,1, equivalent to a spectral Linke turbidity factor of about 2,8. The third column contains the irradiance integrated from 0 to λ , $E_{I(0-\lambda)}$. In the fourth column, the corresponding fractions of total irradiance, $E_{I(0-\infty)}$, are listed.

Table 3 presents these quantities for the same atmospheric parameters except that the spectral optical depth of aerosol extinction is 0,27 which is equivalent to a spectral Linke turbidity factor of about 4,2. Tables 4 and 5 contain the spectral irradiances of global solar

radiation with the same atmospheric conditions as specified for Tables 2 and 3 respectively. Figures 2 a and b give the graphical representations.

3.3 Spectral irradiances based on parameterizations

Computations of spectral irradiances with the help of rigorous radiative transfer models of the atmosphere are rather complicated and time-consuming so that they are not well suited for calculating numerous spectral distributions for a variety of sets of the atmospheric parameters. For this reason, parameterization schemes of various accuracy have been established and used for more than fifty years. Some more recent papers are given in ref. [32, 33, 34, 35, 36]. A valuable review may be found in Iqbal [15].

Probably one of the most reliable parameterization schemes taking into account many recent findings of atmospheric radiation research has recently been published by Justus and Paris [37]. They compared their results with the computational data from Bird and Hulstrom [31], (see Figs.3 a and b) and with the measurements of Kok and Chalmers [38], (see Figs.4 a and b). The agreement is very satisfactory. (Other measured results are given in references 41-43.)

Thus, the parameterized model of Justus and Paris [37] may be recommended as a reliable tool for conveniently computing spectral irradiances of direct normal and global solar radiation for various atmospheric conditions. The model is extensively described in [39] and [40].

The dependence of various parameters of direct and global solar radiation are systematically demonstrated by Figures 5-11. The variation on a horizontal plane is shown in Fig.5. Figure 6 illustrates the influence of different amounts of the absorbing gases ozone and water vapor. In Fig.7, the turbidity expressed as spectral optical depth of the atmosphere with respect to aerosol scattering is varied.

Figures 8-10 give the corresponding diagrams for global solar radiation. Figure 11 shows global solar radiation under overcast skies of various capacities expressed as spectral optical depths of the cloudiness.

The numerical values for each case are compiled in Table 7 for global solar radiation. Table 8 lists the spectral global irradiances under overcast skies.

4. APPENDICES

4.1 Tables 1 to 8.

TABLE 1

Extraterrestrial solar spectral irradiance at mean earth-sun distance [3, 14]

$\Delta\lambda$: wavelength interval in nm

$\Delta E_0(\lambda)$: irradiance in that interval in Wm^{-2}

$E_0 = \Delta E_0(\lambda)/\Delta\lambda$: mean spectral irradiance in that interval, in $\text{Wm}^{-2} \text{ nm}^{-1}$.

$\Delta\lambda$	$\Delta E_0(\lambda)$	$E_0\lambda$	$\Delta\lambda$	$\Delta E_0(\lambda)$	$E_0\lambda$
0 - 250	2,51	-	340 - 342	1,94	0,970
250 - 252	0,13	0,065	342 - 344	1,89	0,945
252 - 254	0,12	0,060	344 - 346	1,66	0,830
254 - 256	0,17	0,085	346 - 348	1,81	0,905
256 - 258	0,27	0,135	348 - 350	1,80	0,900
258 - 260	0,27	0,135	350 - 352	2,02	1,010
260 - 262	0,22	0,110	352 - 354	2,08	1,040
262 - 264	0,32	0,160	354 - 356	2,27	1,135
264 - 266	0,57	0,285	356 - 358	1,70	0,850
266 - 268	0,57	0,285	358 - 360	1,72	0,860
268 - 270	0,55	0,275	360 - 362	2,04	1,020
270 - 272	0,55	0,275	362 - 364	2,16	1,080
272 - 274	0,44	0,220	364 - 366	2,19	1,095
274 - 276	0,37	0,185	366 - 368	2,46	1,230
276 - 278	0,52	0,260	368 - 370	2,35	1,175
278 - 280	0,28	0,140	370 - 372	2,31	1,155
280 - 282	0,37	0,185	372 - 374	1,89	0,945
282 - 284	0,67	0,335	374 - 376	2,07	1,035
284 - 286	0,45	0,225	376 - 378	2,62	1,310
286 - 288	0,72	0,360	378 - 380	2,51	1,255
288 - 290	0,90	0,450	380 - 382	2,33	1,165
290 - 292	1,24	0,620	382 - 384	1,48	0,740
292 - 294	1,13	0,565	384 - 386	2,04	1,020
294 - 296	1,14	0,570	386 - 388	1,93	0,965
296 - 298	1,07	0,535	388 - 390	2,24	1,120
298 - 300	0,99	0,495	390 - 392	2,56	1,280
300 - 302	1,12	0,560	392 - 394	1,49	0,745
302 - 304	1,06	0,530	394 - 396	2,53	1,265
304 - 306	1,09	0,545	396 - 398	1,72	0,860
306 - 308	1,22	0,610	398 - 400	3,21	1,605
308 - 310	1,18	0,590	400 - 402	3,60	1,800
310 - 312	1,31	0,655	402 - 404	3,36	1,680
312 - 314	1,36	0,680	404 - 406	3,27	1,635
314 - 316	1,42	0,710	406 - 408	3,25	1,625
316 - 318	1,44	0,720	408 - 410	3,37	1,685
318 - 320	1,43	0,715	410 - 412	3,45	1,725
320 - 322	1,56	0,780	412 - 414	3,52	1,760
322 - 324	1,36	0,680	414 - 416	3,45	1,725
324 - 326	1,39	0,695	416 - 418	3,56	1,780
326 - 328	2,12	1,060	418 - 420	3,32	1,660
328 - 330	1,99	0,995	420 - 422	3,67	1,835
330 - 332	2,00	1,000	422 - 424	3,29	1,645
332 - 334	1,90	0,950	424 - 426	3,50	1,750
334 - 336	1,87	0,935	426 - 428	3,25	1,625
336 - 338	1,61	0,805	428 - 430	3,05	1,525
338 - 340	1,90	0,950	430 - 432	2,92	1,460

TABLE 1 - continued

$\Delta\lambda$	$\Delta E_0(\lambda)$	$E_0\lambda$	$\Delta\lambda$	$\Delta E_0(\lambda)$	$E_0\lambda$
432 - 434	3,31	1,655	524 - 526	3,88	1,940
434 - 436	3,54	1,770	526 - 528	3,56	1,780
436 - 438	3,70	1,850	528 - 530	3,84	1,920
438 - 440	3,38	1,690	530 - 532	3,95	1,975
440 - 442	3,64	1,820	532 - 534	3,76	1,880
442 - 444	3,90	1,950	534 - 536	3,92	1,960
444 - 446	3,78	1,890	536 - 538	3,81	1,905
446 - 448	3,92	1,960	538 - 540	3,76	1,880
448 - 450	4,03	2,015	540 - 542	3,67	1,835
450 - 452	4,37	2,185	542 - 544	3,78	1,890
452 - 454	3,89	1,945	544 - 546	3,81	1,905
454 - 456	4,06	2,030	546 - 548	3,76	1,880
456 - 458	4,13	2,065	548 - 550	3,84	1,920
458 - 460	3,98	1,990	550 - 552	3,77	1,885
460 - 462	4,15	2,075	552 - 554	3,77	1,885
462 - 464	4,17	2,085	554 - 556	3,82	1,910
464 - 466	3,96	1,980	556 - 558	3,67	1,835
466 - 468	3,91	1,955	558 - 560	3,67	1,835
468 - 470	4,02	2,010	560 - 562	3,69	1,845
470 - 472	3,90	1,950	562 - 564	3,76	1,880
472 - 474	4,04	2,020	564 - 566	3,67	1,835
474 - 476	4,03	2,015	566 - 568	3,70	1,850
476 - 478	4,03	2,015	568 - 570	3,70	1,850
478 - 480	4,12	2,060	570 - 572	3,57	1,785
480 - 482	4,10	2,050	572 - 574	3,74	1,870
482 - 484	4,01	2,005	574 - 576	3,72	1,860
484 - 486	3,83	1,915	576 - 578	3,61	1,805
486 - 488	3,54	1,770	578 - 580	3,64	1,820
488 - 490	3,88	1,940	580 - 582	3,72	1,860
490 - 492	3,80	1,900	582 - 584	3,69	1,845
492 - 494	3,84	1,920	584 - 586	3,62	1,810
494 - 496	3,95	1,975	586 - 588	3,61	1,805
496 - 498	3,98	1,990	588 - 590	3,35	1,675
498 - 499	3,82	1,910	590 - 592	3,62	1,810
500 - 502	3,63	1,815	592 - 594	3,54	1,770
502 - 504	3,84	1,920	594 - 596	3,57	1,785
504 - 506	3,93	1,965	596 - 598	3,60	1,800
506 - 508	3,85	1,925	598 - 600	3,44	1,720
508 - 510	3,88	1,940	600 - 602	3,44	1,720
510 - 512	3,93	1,965	602 - 604	3,55	1,775
512 - 514	3,76	1,880	604 - 606	3,47	1,735
514 - 516	3,77	1,885	606 - 608	3,52	1,760
516 - 518	3,40	1,700	608 - 610	3,39	1,695
518 - 520	3,45	1,725	610 - 612	3,47	1,735
520 - 522	3,76	1,880	612 - 614	3,42	1,710
522 - 524	3,84	1,920	614 - 616	3,42	1,710