



Designation: G 159 – 98

Standard Tables for References Solar Spectral Irradiance at Air Mass 1.5: Direct Normal and Hemispherical for a 37° Tilted Surface¹

This standard is issued under the fixed designation G 159; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reappraisal. A superscript epsilon (ε) indicates an editorial change since the last revision or reappraisal.

INTRODUCTION

These tables use the revised (1)² extraterrestrial spectrum of Neckel and Labs (2). In addition, refinements were made to the calculation of atmospheric absorption and scattering in the computer code (3, 4) used to calculate the spectrum. These refinements consist of a change in the depolarization factor in the Rayleigh scattering calculation, a more accurate sampling technique for calculating scattered irradiance, and a better choice of wavelengths to perform the calculations.

1. Scope

1.1 These tables cover an air mass 1.5 solar spectral irradiance distribution for use in all terrestrial applications in which a standard reference spectral irradiance is required for the direct component of solar irradiance and hemispherical solar irradiance, consisting of both the diffuse and direct components, that is incident on a sun-facing, 37°-tilted surface.

1.2 An air mass of 1.5, a turbidity of 0.27, and a tilt of 37° (for the hemispherical spectral irradiance tables) were chosen for this standard because they are representative of average conditions in the 48 contiguous states of the United States. In real life, a large range of atmospheric conditions can be encountered, resulting in more or less important variations in atmospheric extinction. Thus, considerable departure from the present reference spectra might be observed depending on time of the day, geographical location, and other fluctuating conditions in the atmosphere.

1.3 These tables are an editorial revision of Tables E 891 and Tables E 892, that have been combined. This action has been taken to make the reference solar spectral energy standards harmonious with ISO 9845-1:1992, that was itself based wholly on Tables E 891 and Tables E 892 with respect to the tables of spectral irradiance values. The tables contained here are identical to those contained in Tables E 891 and E 892.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate*

safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards:

E 490 Solar Constant and Air Mass Zero Solar Spectral Irradiance Tables³

E 772 Terminology Relating to Solar Energy Conversion⁴

E 891 Tables for Terrestrial Direct Normal Solar Spectral Irradiance for Air Mass 1.5⁵

E 892 Tables for Terrestrial Solar Spectral Irradiance at Air Mass 1.5 for a 37° Tilted Surface⁵

2.2 ISO Standard:

ISO 9845-1:1992(E) Solar Energy - Reference Solar Spectral Irradiance at the Ground at Different Receiving Conditions - Part 1: Direct Normal and Hemispherical Solar Irradiance for Air Mass 1.5⁶

3. Terminology

3.1 Definitions (from Terminology E 772):

3.1.1 *air mass (AM)*—ratio of the mass of atmosphere in the actual observer-sun path to the mass that would exist if the observer were at sea level, at standard barometric pressure, and the sun were directly overhead.

3.1.1.1 *Discussion*—(Sometimes called air mass ratio.) Air mass varies with the zenith angle of the sun and the local barometric pressure, that changes with altitude. For sun zenith Z , of 62° or less, and local atmospheric pressure, P , where P_0 is standard atmospheric pressure, $AM \cong (P/P_0)\sec Z$.

¹ These tables are under the jurisdiction of ASTM Committee G-03 on Weathering and Durability and is the direct responsibility of Subcommittee G03.09 on Radiometry.

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² The boldface numbers given in parentheses refer to the list of references at the end of the text.

³ *Annual Book of ASTM Standards*, Vol 15.03.

⁴ *Annual Book of ASTM Standards*, Vol 12.02.

⁵ *Annual Book of ASTM Standards*, Vol 14.04.

⁶ Available from American National Standards Institute, 11 W. 42nd St., 13th Floor, New York, NY 10036.

3.1.2 *solar irradiance, diffuse, $E_{s,d}$* —downward scattered solar flux is received on a horizontal surface from a solid angle of 2π -steradian (hemisphere) with the exception of a conical solid angle with a 100 mrad (approximately 6°) included plane angle centered upon the sun's disk.

3.1.3 *solar irradiance, direct, E* —solar flux coming from the solid angle of the sun's disk on a surface perpendicular to the axis of that solid angle.

3.1.3.1 *Discussion*—In conventional instruments, the acceptance cone includes a plane angle of about 6° .

3.2 Definitions of Terms Specific to This Standard:

3.2.1 *air mass zero (AMO)*—describing solar radiation quantities outside the Earth's atmosphere at the mean earth-sun distance.

3.2.2 *solar irradiance, hemispherical, E_H* —on a given plane, the solar radiant flux received from that portion of the hemispherical sky dome included in the plane's field of view, including both diffuse and direct solar irradiance.

3.2.2.1 *Discussion*—For the special condition of a horizontal plane, the hemispherical solar irradiance is properly termed *global solar irradiance, E_G* .

3.2.3 *meteorological optical range*—horizontal distance V at which the contrast between a black target and the sky above the horizon is equal to the threshold contrast ϵ_0 :

$$V = \frac{1}{\sigma} \ln \frac{1}{\epsilon_0} \quad (1)$$

where: σ is the atmospheric extinction coefficient in reciprocal meters, and ϵ_0 is a parameter equal to 0.05; thus:

$$\ln \frac{1}{\epsilon_0} \cong 3.0 \quad (2)$$

3.2.4 *solar irradiance, spectral (E_λ)*—solar irradiance E per unit wavelength interval at a given wavelength λ (unit: watts per square metre per micrometre, $\text{W}\cdot\text{m}^{-2}\cdot\mu\text{m}^{-1}$).

$$E_\lambda = \frac{dE}{d\lambda} \quad (3)$$

4. Technical Bases for These Tables

4.1 These tables are modeled data that were generated using a zero air mass solar spectrum based on the revised extraterrestrial spectrum of Neckel and Labs (1), the BRITE (3,4) Monte Carlo radiative transfer code, and the 1962 U.S. Standard Atmosphere (5) with a rural aerosol (6-8). Further details are presented in Appendix X1.

4.2 The air mass zero (AMO) spectrum that was used to generate the terrestrial spectrum was provided by C. Fröhlich and C. Wehrli (1) and is a revised and extended Neckel and Labs (2) spectrum. Neckel and Labs revised their spectrum by using newer limb-darkening data to convert from radiance to irradiance, as reported by Fröhlich (9), citing the study by Hardrop (10). Comparisons by Fröhlich with calibrated sun-photometer data from Mauna Loa, Hawaii, indicated that this new extraterrestrial spectrum is the best that was then available.

4.3 The development of the terrestrial solar spectrum data is based on work reported by Bird, Hulstrom, and Lewis (11). In computing the terrestrial values using the BRITE Monte Carlo radiation transfer code, the authors cited took the iterations to 24 500 μm only. This spectrum has been later extended to 4045 μm using 16 E_{λ_i} values from the original Tables E 892. Irradiance values in Tables E 892 were computed from the extraterrestrial spectrum represented by Tables E 490. The additional data points were added to account for the solar irradiance in this region that represent approximately 1.5 % of the total irradiance between 0.305 and 4.045 μm . The errors propagated by doing so are insignificant.

5. Significance and Use

5.1 Absorptance, reflectance, and transmittance of solar energy are important factors in solar thermal system performance, photovoltaic system performance, materials studies, biomass studies, and solar simulation activities. These optical properties are normally functions of wavelength, which requires that the spectral distribution of the solar flux be known before the solar weighted property can be calculated. To compare the performance of competitive products, or to compare the performance of products before and after being subjected to weathering or other exposure conditions, a reference standard solar spectral irradiance distribution is desirable.

5.2 These tables provide an appropriate standard spectral irradiance distribution to be used in determining relative performance of solar thermal, photovoltaic, and other systems, components, and materials and for the purposes of solar simulation in which the direct irradiance component is desired (see Columns 2 through 4 of Table 1), or direct plus diffuse irradiance components are desired (see Columns 5 through 7 of Table 1).

TABLE 1 Spectral Solar Irradiance

Wavelength λ_i	Direct Normal Solar Spectral Irradiance from 0.305 0 to 4.045 0 μm			Hemispherical Solar Spectral Irradiance Incident on a 37° Tilted Plane, Equator-Facing			Normalized Solar Spectral Hemispherical Irradiance (Normalized to 1 000 $\text{W}\cdot\text{m}^{-2}$)		
	E_{λ_i}	$F_{0 \rightarrow \lambda_i}$	F_{λ_i}	E_{λ_i}	$E_{0 \rightarrow \lambda_i}$	F_{λ_i}	F_{λ_i}	$F_{0 \rightarrow \lambda_i}$	F_{λ_i}
1	2	3	4	5	6	7	8	9	10
0.035 0	3.4	0.02	0.000 0	9.2	0.06	0.000 1	9.5	0.06	0.000 1
0.310 0	15.6	0.07	0.000 1	40.8	0.19	0.000 2	42.3	0.19	0.000 2
0.315 0	41.1	0.21	0.000 3	103.9	0.55	0.000 6	107.8	0.57	0.000 6
0.320 0	71.2	0.49	0.000 6	174.4	1.25	0.001 3	181.0	1.29	0.001 3
0.325 0	100.2	0.92	0.001 2	237.9	2.28	0.002 4	246.0	2.36	0.002 4
0.330 0	152.4	1.55	0.002 0	381.0	3.82	0.004 0	395.3	3.97	0.004 0



TABLE 1 Continued

Wavelength λ_i	Direct Normal Solar Spectral Irradiance from 0.305 0 to 4.045 0 μm			Hemispherical Solar Spectral Irradiance Incident on a 37° Tilted Plane, Equator-Facing			Normalized Solar Spectral Hemispherical Irradiance (Normalized to 1 000 W·m ⁻²)		
	E_{λ_i}	$F_{0 \rightarrow \lambda_i}$	F_{λ_i}	E_{λ_i}	$E_{0 \rightarrow \lambda_i}$	F_{λ_i}	F_{λ_i}	$F_{0 \rightarrow \lambda_i}$	F_{λ_i}
1	2	3	4	5	6	7	8	9	10
0.335 0	155.6	2.32	0.003 0	376.0	5.72	0.005 9	390.1	5.93	0.005 9
0.340 0	179.4	3.16	0.004 1	419.5	7.70	0.008 0	435.3	7.99	0.008 0
0.345 0	186.7	4.08	0.005 3	423.0	9.81	0.010 2	438.9	10.18	0.010 2
0.350 0	212.0	5.07	0.006 6	466.2	12.03	0.012 5	483.7	12.40	0.012 5
0.360 0	240.5	7.34	0.009 5	501.4	16.87	0.017 5	520.3	17.51	0.017 5
0.370 0	324.0	10.16	0.013 2	642.1	22.59	0.023 4	666.2	23.44	0.023 4
0.380 0	362.4	13.59	0.017 7	686.7	29.23	0.030 3	712.5	30.33	0.030 3
0.390 0	381.7	17.31	0.022 5	649.6	36.14	0.037 5	720.7	37.50	0.037 5
0.400 0	556.0	22.00	0.028 6	976.4	44.49	0.046 2	1 013.1	46.17	0.046 2
0.410 0	656.3	28.06	0.036 5	1 116.2	54.96	0.057 0	1 158.2	57.02	0.057 0
0.420 0	690.8	34.80	0.045 3	1 141.1	66.24	0.068 7	1 184.0	68.74	0.068 7
0.430 0	641.9	41.46	0.054 0	1 033.0	77.11	0.080 0	1 071.9	80.01	0.080 0
0.440 0	798.5	48.66	0.063 3	1 254.8	88.55	0.091 9	1 302.0	91.88	0.091 9
0.450 0	956.6	57.44	0.074 8	1 470.7	102.18	0.106 0	1 526.0	106.02	0.106 0
0.460 0	990.8	67.17	0.087 4	1 541.6	117.24	0.121 7	1 599.6	121.65	0.121 7
0.470 0	998.0	77.12	0.100 4	1 523.7	132.57	0.137 6	1 581.0	137.55	0.137 6
0.480 0	1 046.1	87.34	0.113 7	1 569.3	148.03	0.153 6	1 628.3	153.60	0.153 6
0.490 0	1 005.1	97.59	0.127 0	1 483.4	163.30	0.169 4	1 539.2	169.44	0.169 4
0.500 0	1 026.7	107.75	0.140 2	1 492.6	178.18	0.184 9	1 548.7	184.88	0.184 9
0.510 0	1 066.7	118.22	0.153 9	1 529.0	193.29	0.200 6	1 586.5	200.55	0.200 6
0.520 0	1 011.5	128.61	0.167 4	1 431.1	208.09	0.215 9	1 484.9	215.91	0.215 9
0.530 0	1 084.9	139.89	0.181 0	1 515.4	222.82	0.231 2	1 572.4	231.20	0.231 2
0.540 0	1 082.4	149.93	0.195 1	1 494.5	237.87	0.246 8	1 550.7	246.81	0.246 8
0.550 0	1 102.2	160.85	0.209 4	1 504.9	252.87	0.262 4	1 561.5	262.38	0.262 4
0.570 0	1 087.4	182.75	0.237 9	1 447.1	282.39	0.293 0	1 501.5	293.01	0.293 0
0.590 0	1 024.3	203.87	0.265 3	1 344.9	310.30	0.322 0	1 395.5	321.98	0.322 0
0.610 0	1 088.8	225.00	0.292 8	1 431.5	338.07	0.350 8	1 485.3	350.78	0.350 8
0.630 0	1 062.1	246.51	0.320 8	1 382.1	366.20	0.380 0	1 434.1	379.98	0.380 0
0.650 0	1 061.7	267.74	0.348 5	1 368.4	393.71	0.408 5	1 419.9	408.52	0.408 5
0.670 0	1 046.2	288.82	0.375 9	1 341.8	420.81	0.436 6	1 392.3	436.64	0.436 6
0.690 0	859.2	307.88	0.400 7	1 089.0	445.12	0.461 9	1 130.0	461.86	0.461 9
0.710 0	1 002.4	326.49	0.424 9	1 269.0	468.70	0.486 3	1 316.7	486.33	0.486 3
0.718 0	816.9	333.77	0.434 4	973.7	477.87	0.495 6	1 010.3	495.64	0.495 6
0.724 4	842.8	339.08	0.441 3	1 005.4	484.00	0.502 2	1 043.2	502.21	0.502 2
0.740 0	971.0	353.23	0.459 7	1 167.3	500.95	0.519 8	1 211.2	519.79	0.519 8
0.752 5	956.3	365.27	0.475 4	1 150.6	515.44	0.534 8	1 193.9	534.82	0.534 8
0.757 5	942.2	378.82	0.481 6	1 132.9	521.15	0.540 7	1 175.5	540.75	0.540 7
0.762 5	524.8	373.69	0.486 4	619.8	525.53	0.545 3	643.1	545.29	0.545 3
0.767 5	830.7	377.08	0.490 8	993.3	529.56	0.549 5	1 030.7	549.48	0.549 5
0.780 0	908.9	387.95	0.504 9	1 090.1	542.58	0.563 0	1 131.1	562.99	0.563 0
0.800 0	873.4	405.77	0.528 1	1 042.4	563.91	0.585 1	1 081.6	585.12	0.585 1
0.816 0	712.0	418.46	0.544 6	818.4	578.79	0.600 6	849.2	600.56	0.600 6
0.823 7	660.2	423.74	0.551 5	756.5	584.86	0.606 9	785.0	606.85	0.606 9
0.831 5	765.5	429.30	0.558 0	883.2	591.25	0.613 5	916.4	613.49	0.613 5
0.840 0	799.8	435.95	0.567 4	925.1	598.94	0.621 5	959.9	621.46	0.621 5
0.860 0	815.2	452.10	0.588 4	943.4	617.62	0.640 9	978.9	640.85	0.640 9
0.880 0	778.3	468.04	0.609 2	899.4	636.05	0.660 0	933.2	659.97	0.660 0
0.905 0	630.4	485.65	0.632 1	721.4	656.31	0.681 0	748.5	680.99	0.681 0
0.915 0	565.2	491.62	0.639 9	643.3	663.13	0.688 1	667.5	688.07	0.688 1
0.925 0	586.4	497.38	0.647 4	665.3	669.68	0.694 9	690.3	694.86	0.694 9
0.930 0	348.1	499.72	0.650 4	389.0	672.31	0.697 6	403.6	697.60	0.697 6
0.937 0	224.2	501.72	0.653 0	248.9	674.55	0.699 9	258.3	699.91	0.699 9
0.948 0	271.4	504.45	0.656 6	302.2	677.58	0.703 1	313.6	703.06	0.703 1
0.965 0	451.2	510.59	0.664 6	507.7	684.46	0.710 2	526.8	710.20	0.710 2
0.980 0	549.7	518.10	0.674 3	623.0	692.94	0.719 0	646.4	719.00	0.719 0
0.993 5	630.1	526.06	0.684 7	719.7	702.00	0.728 4	746.8	728.41	0.728 4
1.040 0	582.9	554.26	0.721 4	665.5	734.21	0.761 8	690.5	761.82	0.761 8