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AMERICAN SOCIETY FOR TESTING AND MATERIALS
100 Barr Harbor Dr., West Conshohocken, PA 19428

Standard Tables for References Solar Spectral Irradiance at Air Mass 1.5: Direct Normal and Hemispherical for a 37° Tilted Surface[1]

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 reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

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 Tables[3]

E 772 Terminology Relating to Solar Energy Conversion[4]

E 891 Tables for Terrestrial Direct Normal Solar Spectral Irradiance for Air Mass 1.5[5]

E 892 Tables for Terrestrial Solar Spectral Irradiance at Air Mass 1.5 for a 37° Tilted Surface[5]

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 1.5[6]

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_O is standard atmospheric pressure, $AM \cong (P/P_O)\sec Z$.

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.

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[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.

3.1.3 *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_O:

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

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, $W \cdot m^{-2} \cdot \mu m^{-1}$).

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

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 (AM0) 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 sunphotometer 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 $E\lambda_i$ 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	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 $W \cdot m^{-2}$		
λ_i	E_{λ_i}	$F_{0\rightarrow\lambda_i}$	$F_{\lambda i}$	E_{λ_i}	$E_{0 \cdot \lambda_i}$	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
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

TABLE 1 *Continued*

Wavelength	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}		
λ_i	E_{λ_i}	$F_{0\rightarrow\lambda_i}$	$F_{\lambda i}$	E_{λ_i}	$E_{0\,\cdot\lambda_i}$	F_{λ_i}	$F\cdot_{\lambda_i}$	$F\cdot_{0\rightarrow\lambda_i}$	F_{λ_i}
1	2	3	4	5	6	7	8	9	10
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	0.583 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	0.813 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
1.070 0	539.7	571.10	0.743 3	614.4	753.41	0.781 7	637.5	781.74	0.781 7
1.100 0	366.2	584.69	0.761 0	397.6	768.59	0.797 5	412.6	797.49	0.797 5

TABLE 1 *Continued*

Wavelength	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^)		
λ_i	E_{λ_i}	$F_{0\to\lambda_i}$	$F_{\lambda i}$	E_{λ_i}	$E_{0\cdot\lambda_i}$	F_{λ_i}	F'_{λ_i}	$F'_{0\to\lambda_i}$	F_{λ_i}
1	2	3	4	5	6	7	8	9	10
1.120 0	98.1	589.33	0.767 0	105.0	773.61	0.802 7	108.9	802.71	0.802 7
1.130 0	169.5	590.67	0.768 8	182.2	775.05	0.804 2	189.1	804.20	0.804 2
1.137 0	118.7	591.68	0.770 1	127.4	776.13	0.805 3	132.2	805.32	0.805 3
1.161 0	301.9	596.73	0.776 7	326.7	781.58	0.811 0	339.0	810.98	0.811 0
1.180 0	406.8	603.46	0.785 4	443.3	788.90	0.818 6	460.0	818.57	0.818 6
1.200 0	375.2	611.28	0.795 6	408.2	797.41	0.827 4	423.6	827.40	0.827 4
1.235 0	423.6	625.26	0.813 8	463.1	812.66	0.843 2	480.5	843.22	0.843 2
1.290 0	365.7	546.96	0.842 1	398.1	836.34	0.867 8	413.1	867.80	0.867 8
1.320 0	223.4	655.80	0.853 6	241.1	845.93	0.877 7	250.2	877.75	0.877 7
1.350 0	30.1	659.60	0.858 5	31.3	850.02	0.882 0	32.5	881.99	0.882 0
1.395 0	1.4	660.31	0.859 4	1.5	850.76	0.882 8	1.6	882.95	0.882 8
1.442 5	51.6	661.57	0.861 1	53.7	852.07	0.884 1	55.7	884.11	0.884 1
1.462 5	97.0	663.06	0.863 0	101.3	853.62	0.885 7	105.1	885.72	0.885 7
1.477 0	97.3	664.46	0.864 8	101.7	855.09	0.887 2	105.5	887.25	0.887 2
1.497 0	167.1	667.11	0.868 3	175.5	857.86	0.890 1	182.1	890.12	0.890 1
1.520 0	239.3	661.78	0.874 4	253.1	862.79	0.895 2	262.6	895.25	0.895 2
1.539 0	248.8	676.42	0.880 4	264.3	867.70	0.900 3	274.2	900.34	0.900 3
1.558 0	249.3	681.15	0.886 6	265.0	872.73	0.905 6	275.0	905.56	0.905 6
1.578 0	222.3	685.87	0.892 7	235.7	877.74	0.910 8	244.6	910.75	0.910 8
1.592 0	227.3	689.01	0.896 8	238.4	881.06	0.914 2	247.4	914.19	0.914 2
1.610 0	210.5	692.95	0.901 9	220.4	885.19	0.918 5	228.7	918.48	0.918 5
1.630 0	224.7	697.31	0.907 6	235.6	889.75	0.923 2	244.5	923.21	0.923 2
1.646 0	215.9	700.83	0.912 2	226.3	893.44	0.927 0	234.8	927.85	0.927 0
1.678 0	202.8	707.53	0.920 9	212.5	900.46	0.934 3	220.5	934.33	0.934 3
1.740 0	158.2	718.72	0.935 5	165.3	912.18	0.946 5	171.5	946.48	0.946 5
1.800 0	28.6	724.33	0.942 8	29.6	918.02	0.952 5	30.7	952.55	0.952 5
1.860 0	1.8	725.24	0.943 9	1.9	918.97	0.953 5	2.0	953.53	0.953 5
1.920 0	1.1	725.32	0.944 1	1.2	919.06	0.953 6	1.2	953.63	0.953 6
1.960 0	19.7	725.74	0.944 6	20.4	919.49	0.954 1	21.2	954.07	0.954 1
1.985 0	84.9	727.05	0.946 3	87.8	920.85	0.955 5	91.1	955.48	0.955 5
2.005 0	25.0	728.15	0.947 7	25.8	921.98	0.956 7	26.8	956.68	0.956 7
2.035 0	92.5	729.91	0.950 0	95.9	923.81	0.958 6	99.5	958.55	0.958 6
2.065 0	56.3	732.14	0.952 9	58.2	926.12	0.960 9	60.4	960.95	0.960 9
2.100 0	82.7	734.57	0.956 1	85.9	928.64	0.963 6	89.1	963.57	0.963 6
2.148 0	76.2	738.39	0.961 1	79.2	932.60	0.967 7	82.2	967.68	0.967 7
2.198 0	66.4	741.95	0.965 7	68.9	936.30	0.971 5	71.5	971.52	0.971 5
2.270 0	65.0	746.68	0.971 9	67.7	941.22	0.976 6	70.2	976.62	0.976.6
2.360 0	57.6	752.20	0.979 0	59.8	946.96	0.982 6	62.0	982.57	0.982 6
2.450 0	19.8	755.68	0.983 6	20.4	950.52	0.986 3	21.2	986.32	0.986 3
2.494 0	17.0	756.49	0.984 6	17.8	951.41	0.987 2	18.5	987.19	0.987 2
2.537 0	3.0	756.92	0.985 2	3.1	951.86	0.987 7	3.2	987.66	0.987 7
2.941 0	4.0	758.34	0.987 0	4.2	953.33	0.989 2	4.4	989.19	0.989 2
2.973 0	7.0	758.51	0.987 2	7.3	953.52	0.989 4	7.6	989.38	0.989 4
3.005 0	6.0	758.72	0.987 5	6.3	953.73	0.989 6	6.5	989.60	0.989 6
3.056 0	3.0	758.95	0.987 8	3.1	953.97	0.989 9	3.2	989.85	0.989 9
3.132 0	5.0	759.25	0.988 2	5.2	954.29	0.990 2	5.4	990.18	0.990 2
3.156 0	18.0	759.53	0.988 6	18.7	954.58	0.990 5	19.4	990.48	0.990 5
3.204 0	1.2	759.99	0.989 2	1.3	955.06	0.991 0	1.3	990.98	0.991 0
3.245 0	3.0	760.08	0.989 3	3.1	955.15	0.991 1	3.2	991.07	0.991 1
3.317 0	12.0	760.92	0.990 0	12.6	955.71	0.991 7	13.1	991.66	0.991 7
3.344 0	3.0	760.82	0.990 2	3.1	955.92	0.991 9	3.2	991.88	0.991 9
3 450 0	12.2	761.62	0.991 3	12.8	956.77	0.992 8	13.3	992.75	0.992 8
3.573 0	11.0	763.05	0.993 2	11.5	958.26	0.994 3	11.9	994.30	0.994 3
3.765 0	9.0	764.97	0.995 7	9.4	960.27	0.996 4	9.8	996.38	0.996 4
4.045 0	6.9	767.20	0.998 6	7.2	962.59	0.998 8	7.5	998.79	0.998 9
>4.045 0	. . .	768.31	1.000 0	. . .	963.75	1.000 0	. . .	1000.00	1.000 0

6. Solar Spectral Irradiance (Air Mass 1.5)

6.1 The tables present the standard reference spectral irradiance data for direct normal, hemispherical, and normalized hemispherical solar irradiance.

6.2 Table 1 contains:

6.2.1 Direct normal solar spectral irradiance in the wavelength range from 0.3050 to 4.0450 µm (that is: from 305 to 4045 nm).

6.2.2 Hemispherical solar spectral irradiance incident on an equator-facing[7] plane tilted to 37° from the horizontal in the wavelength range from 0.3050 to 4.0450 µm.

6.2.3 Normalized hemispherical solar spectral irradiance on an equator-facing plane tilted to 37° from the horizontal (normalized to a solar irradiance of 1000 $W \cdot m^{-2}$) in the wavelength range from 0.3050 to 4.0450 µm.

6.2.4 The values in Table 1 relate to an air mass of 1.5 (AM = 1.5) between the observer (the surface plane) and the sun. For direct irradiance, the data closely approximates a field of view of 5.8°.

6.2.5 The columns in Table 1 give the tabular spectral irradiance data for the following parameters:

6.2.5.1 Column 1: wavelength λ in µm;

6.2.5.2 Columns 2, 5, and 8: the mean value of spectral irradiance E_λ in watts per square metre per micrometre, $W \cdot m^{-2} \cdot \mu m^{-1}$;

6.2.5.3 Columns 3, 6, and 9: integrated solar irradiance $E_{0-\lambda i}$ in watts per square metre, $W \cdot m^{-2}$;

6.2.5.4 Columns 4, 7, and 10: the fraction $F_{\lambda i}$ of solar irradiance in the wavelength range 0 to λ_i.

NOTE 1—There is an insignificant amount of radiation reaching the earth's surface at wavelengths below 0.3 µm. See also the plots of solar irradiance in Fig. X3.1 and Fig. X3.2.

6.3 Table 2 presents 100 selected ordinates for:

6.3.1 Direct normal solar spectral irradiance in the spectral range from 0.3050 to 4.0450 µm incident on a tilted plane oriented at normal incidence to the direct component;

6.3.2 Hemispherical solar spectral irradiance incident on a 37° tilted plane facing the equator.

6.3.3 The columns in Table 2 give the values for the following parameters:

6.3.3.1 Column 1: the fraction $F_{\lambda k}$ of solar irradiance in the wavelength range 0 to λ_k;

6.3.3.2 Columns 2 and 4: integrated solar irradiance $E_{0-\lambda k}$ in watts per square metre, $W \cdot m^{-2}$;

6.3.3.3 Columns 3 and 5: wavelength λ_k in micrometres µm.

6.3.4 Table 3 presents the tabular data for 50 selected ordinates. The parameters in Table 3 are the same as those given in Table 2.

[7] South facing for the Northern Hemisphere.

TABLE 2 100 Selected Ordinates for, at AM = 1.5, (a) Direct Normal Irradiance (Field-of-View Angle = 5.8°) and (b) Hemispherical Irradiance Incident on a 37° Tilted Plane, Equator-Facing (Ground Albedo 0.2)

Wavelength Fraction	(a) Direct Normal Irradiance		(b) Hemispherical Irradiance	
F_{λ_k}	$F_{0\rightarrow\lambda_k}$	λ_k	$F_{0\rightarrow\lambda_k}$	λ_k
1	2	3	4	5
0.005	3.841 6	0.343 7	4.818 8	0.332 6
0.015	11.524 7	0.374 0	14.456 3	0.355 0
0.025	19.207 8	0.394 0	24.093 8	0.372 3
0.035	26.890 9	0.408 1	33.731 3	0.386 5
0.045	34 574 0	0.419 7	43.368 8	0.398 7
0.055	42.257 1	0.431 1	53.006 3	0.408 1
0.065	49.940 2	0.441 5	62.643 8	0.416 8
0.075	57 623 3	0.450 2	72 281 2	0.425 6
0.085	65 306 3	0.458 1	81.918 7	0.434 2
0.095	72.989 5	0.465 8	91.556 2	0.442 2
0.105	80 672 5	0.473 5	101.193 0	0.449 3
0.115	88.355 6	0.481 0	110.831 3	0.455 7
0.125	96 038 7	0.488 5	120.468 8	0.462 1
0.135	103.721 9	0.496 0	130.106 3	0.468 4
0.145	111.405 0	0.503 5	139.743 8	0.474 6
0.155	119.088 1	0.510 8	149.381 3	0.480 9
0.165	126.771 2	0.518 2	159.018 8	0.487 2
0.175	134.454 3	0.525 6	168.656 3	0.493 6
0.185	142.137 4	0.532 8	178.293 8	0.500 1
0.195	149.820 5	0.539 9	187.931 3	0.506 5
0.205	157.503 6	0.546 9	197.568 8	0.512 9
0.215	165.186 7	0.554 0	207.206 3	0.519 4
0.225	172.869 8	0.561 0	216.843 8	0.525 9
0.235	180.552 9	0.568 0	226.481 3	0.532 4
0.245	188.236 0	0.575 2	236.118 8	0.538 8
0.255	195.919 1	0.582 5	245.756 3	0.545 3
0.265	203.602 2	0.589 7	255.393 8	0.551 7
0.275	211.285 3	0.597 0	265.031 3	0.558 2
0.285	218.968 4	0.604 3	274.668 8	0.564 8
0.295	226.651 5	0.611 5	284.306 3	0.571 4
0.305	234.334 6	0.618 7	293.943 8	0.578 3
0.315	242.017 7	0.625 8	303 581 3	0.585 2
0.325	249.700 8	0.633 0	313.218 8	0.592 1
0.335	257.383 9	0.640 2	322.856 3	0.599 0
0.345	265.067 0	0.647 5	332.493 8	0.606 0
0.355	272.750 1	0.654 8	342.131 3	0.612 9
0.365	280.433 2	0.662 0	351.768 8	0.619 7
0.375	288.116 3	0.669 3	361.406 3	0.626 6
0.385	295.799 4	0.677 3	371.043 7	0.633 5
0.395	303.482 5	0.685 4	480.681 3	0.640 5
0.405	311.165 6	0.693 5	390.318 8	0.647 5
0.415	318.848 7	0.701 8	399.956 3	0.654 6
0.425	326.531 8	0.710 0	409.593 7	0.661 7
0.435	334.214 9	0.718 5	419.231 2	0.668 8
0.445	341.898 0	0.727 5	428.868 7	0.676 6
0.455	349.581 1	0.736 0	438.506 2	0.684 6
0.465	357.264 2	0.744 2	448.143 7	0.692 6
0.475	364.947 3	0.752 2	457.781 2	0.700 7
0.485	372.630 4	0.761 1	467.418 7	0.708 9
0.495	380.313 5	0.771 2	477.056 2	0.717 5
0.505	387.996 5	0.780 1	486.693 7	0.726 9
0.515	395.679 6	0.788 7	496.331 2	0.735 7
0.525	403.362 7	0.797 3	505.968 7	0.744 3
0.535	411.045 8	0.806 7	515.606 2	0.752 6
0.545	418.728 9	0.816 4	525.243 7	0.762 2
0.555	426.412 0	0.827 4	534.881 2	0.772 6

TABLE 2 *Continued*

Wavelength Fraction	(a) Direct Normal Irradiance		(b) Hemispherical Irradiance	
F_{λ_k}	$F_{0\rightarrow\lambda_k}$	λ_k	$F_{0\rightarrow\lambda_k}$	λ_k
1	2	3	4	5
0.565	434.095 1	0.837 6	544.518 7	0.781 8
0.575	441.778 2	0.847 2	554.156 2	0.790 9
0.585	449.461 3	0.856 7	563.793 7	0.799 9
0.595	457.144 4	0.866 3	573.431 2	0.810 2
0.605	464.827 5	0.876 0	583.068 7	0.821 4
0.615	472.510 6	0.886 3	592.706 2	0.833 1
0.625	480.193 7	0.897 3	602.343 7	0.843 6
0.635	487.876 3	0.908 7	611.981 2	0.854 0
0.645	495.559 9	0.921 8	621.618 7	0.864 3
0.655	503.243 0	0.943 1	631.256 2	0.874 8
0.665	510.926 1	0.965 7	640.893 7	0.886 0
0.675	518.609 2	0.980 9	650.531 2	0.897 9
0.685	526.292 3	0.993 9	660.168 7	0.910 7
0.695	533.975 4	1.006 6	669.806 2	0.925 2
0.705	541.658 5	1.019 2	679.443 7	0.952 6
0.715	549.341 6	1.031 9	689.081 2	0.973 2
0.725	557.024 7	1.044 9	698.718 7	0.988 6
0.735	564.707 8	1.058 6	708.356 2	1.002 7
0.745	572.390 9	1.072 8	717.993 7	1.016 6
0.755	580.074 0	1.089 8	727.631 2	1.030 5
0.765	587.757 1	1.113 2	737.268 7	1.044 8
0.775	595.440 2	1.154 9	746.906 2	1.059 8
0.785	603.123 3	1.179 0	756.543 7	1.076 2
0.795	610.806 4	1.198 8	766.181 2	1.095 2
0.805	618.489 5	1.218.0	775.818 7	1.135 0
0.815	626.172 6	1.237 3	785.456 2	1.171 1
0.825	633.855 7	1.256 8	795.093 7	1.194 6
0.835	641.538 8	1.276 3	804.731 2	1.216 8
0.845	649.221 9	1.297 7	814.368 7	1.239 0
0.855	659.905 0	1.328 7	824.006 2	1.261 4
0.865	664.588 1	1.478 0	833.643 7	1.283 7
0.875	672.271 2	1.522 0	843.281 2	1.311 7
0.885	679.954 3	1.553 2	852.918 7	1.453 5
0.895	687.637 4	1.585 9	862.556 2	1.518 9
0.905	695.320 5	1.620 9	872.193 7	1.556 0
0.915	703.003 6	1.656 4	881.831 2	1.595 4
0.925	710.686 7	1.695 5	891.468 7	1.637 5
0.935	718.369 8	1.738 1	901.106 2	1.681 4
0.945	726.052 9	1.966 0	910.743 7	1.732 4
0.955	733.736 0	2.088 0	920.381 2	1.976 4
0.965	741.419 1	2.190 5	930.018 7	2.116 7
0.975	749.102 2	2.309 5	939 656 2	2.247 1
0.985	756.785 3	2.523 5	949.293 7	2.418 2
0.995	764.468 4	3.714 8	958.931 2	3.637 1

TABLE 3 50 Selected Ordinates for, at AM = 1.5, (a) Direct Normal Irradiance (Field-of-View Angle = 5.8°) and (b) Hemispherical Irradiance Incident on a 37° Tilted Plane, Equator-Facing (Ground Albedo 0.2)

Wave-Length Fraction	(a) Direct Normal Irradiance		(b) Hemispherical Irradiance	
F_{λ_k}	$F_{0\rightarrow\lambda_k}$	λ_k	$F_{0\rightarrow\lambda_k}$	λ_k
1	2	3	4	5
0.010	7.683 1	0.361 2	9.637 5	0.344 6
0.030	23.049 3	0.401 7	28.912 5	0.379 5
0.050	38.415 5	0.425 4	48.187 5	0.403 5
0.070	53.781 7	0.445 8	67.462 5	0.421 1
0.090	69.147 9	0.462 0	86.737 5	0.438 4
0.110	84.514 1	0.477 2	106.012 5	0.452 5
0.130	99.880 3	0.492 3	125.287 5	0.465 2
0.150	115.246 5	0.507 2	144.562 5	0.477 8
0.170	130.612 7	0.521 9	163.832 5	0.490 4
0.190	145.978 9	0.536 4	183.112 5	0.503 3
0.210	161.345 1	0.550 5	202.387 5	0.516 1
0.230	176.711 3	0.564 5	221.662 5	0.529 2
0.250	192.077 5	0.578 8	240.937 5	0.542 0
0.270	207.443 7	0.593 4	260.212 5	0.555 0
0.290	222.809 9	0.607 9	279.487 5	0.568 0
0.310	238.176 1	0.622 3	298.762 5	0.581 7
0.330	253.542 3	0.636 6	318.037 5	0.595 6
0.350	268.908 5	0.651 1	337.312 5	0.609 5
0.370	284.274 7	0.665 7	356.587 5	0.623 2
0.390	299.640 9	0.681 4	375.862 5	0.637 0
0.410	315.007 1	0.697 7	395.137 5	0.651 1
0.430	330.373 3	0.714 3	414.412 5	0.665 3
0.450	345.739 5	0.731 7	433.687 5	0.680 6
0.470	361.105 7	0.748 2	452.962 5	0.696 7
0.490	376.471 9	0.766 6	472.237 5	0.713 2
0.510	391.838 1	0.784 4	491.512 5	0.731 3
0.530	407.204 3	0.801 8	510.787 5	0.748 5
0.550	422.570 5	0.822 0	530.062 5	0.768 0
0.570	437.936 7	0.842 5	549.337 5	0.786 3
0.590	453.302 9	0.861 5	568.612 5	0.805 1
0.610	468.669 1	0.880 9	587.887 5	0.827 4
0.630	484.035 3	0.902 7	607.162 5	0.848 8
0.650	499.401 5	0.929 3	626.437 5	0.869 6
0.670	514.767 7	0.973 3	645.712 5	0.891 9
0.690	530.133 9	1.000 2	664.987 5	0.917 8
0.710	545.500 1	1.025 6	684.262 5	0.964 5
0.730	560.866 3	1.051 8	703.537 5	0.995 7
0.750	576.232 5	1.081 3	722.812 5	1.023 5
0.770	591.598 7	1.136 4	742.087 5	1.052 3
0.790	606.964 9	1.189 0	761.362 5	1.085 7
0.810	622.331 1	1.227 7	780.637 5	1.156 8
0.830	637.697 3	1.268 5	799.912 5	1.205 7
0.850	653.063 5	1.310 7	819 187 5	1.250 2
0.870	668.429 7	1.503 5	838.462 5	1.296 6
0.890	683.795 9	1.569 2	857.737 5	1.496 1
0.910	699.162 1	1.638 4	877.012 5	1.575 1
0.930	714.528 3	1.716 8	896.287 5	1.659 0
0.950	729.894 5	2.034 2	915.562 5	1.774 8
0.970	745.260 7	2.248 4	934.837 5	2.178 2
0.990	760.626 9	3.317 9	954.112 5	3.089 8

7. Application of the Spectral Data to the Derivation of Effective Optical Properties

7.1 *Spectrally Modified Total Solar Irradiance*:

7.1.1 If $R(\lambda)$ is the wavelength-dependent property of a device (such as responsivity, transmittance, reflectance, absorptance) and $E_\lambda(\lambda)$ represents the solar spectral irradiance, then E_S, the effective total solar irradiance weighted with the spectral property of this device, can be calculated as an integral of the product of $E_\lambda(\lambda)$ and $R(\lambda)$.

$$E_S = \int_0^\infty R(\lambda)\, E_\lambda d\lambda \quad (4)$$

7.2 *Solar Spectrum Weighting*:

7.2.1 The mean value R_s of the property $R(\lambda)$, that is effective if the total solar spectrum is applied, can in general be calculated by the following equation:

$$R_s = \frac{\int_0^\infty R(\lambda)\, E_\lambda \, d\lambda}{\int_0^\infty E_\lambda \, d\lambda} \quad (5)$$

7.2.2 Since the spectral property and the spectral irradiance are usually known only as discrete values,[8] the integration must be performed as summations so that Eq 4 and 5 become, respectively,

$$E_S = \sum_{i=1}^{N} R(\lambda_i)\, E_{\lambda_i}\, \Delta\lambda_i \quad (6)$$

and:

$$R_S = \frac{E_S}{\sum_{i=1}^{N} E_{\lambda_i}\, \Delta\lambda} \quad (7)$$

where: λ_i is the wavelength of the *i*th point out of N for which the spectral data are known. The values represent the practical limits of the summation.

7.3 *Weighted Ordinate Method*—The summations are performed as indicated in Eq 6 and Eq 7 by using the values of λ_i, $\Delta\lambda_i$, and $E_{\lambda i}$ given in Table 1. Interpolation between nearby values of the spectral response, $R(\lambda)$, is often required since the wavelengths of the digitally recorded response curves may differ from those given in the table.

7.4 *Selected Ordinate Method*:

7.4.1 In the selected ordinate method, the solar spectral irradiance is divided into m wavelength intervals, each containing $1/m$ of the total solar irradiance, $E_{0-\infty}$ and having a centroid wavelength λ_i. This results in all the products $E_{\lambda i}\Delta\lambda_i$ being equal to $E_{0-\infty}/m$, allowing them to be factored from the summation. Eq 6 and Eq 7, respectively, reduce to the following:

[8] That is, they are not usually known as algebraic expressions or algorithms.

$$E_S = \frac{E_{0-\infty}}{m} \sum_{i=1}^{m} R(\lambda_i) \quad (8)$$

and:

$$R_S = \frac{1}{m} \sum_{i=1}^{m} R(\lambda_i) \quad (9)$$

7.4.2 Appropriate values for the centroid wavelengths for 100 and 50 selected ordinates are provided in Table 2 and Table 3. For devices with spectral responses that are relatively smooth, the 50-point selected ordinates are adequate. For devices with spectral responses that contain complex structure, the 100-point selected ordinate or weighted ordinate method should be used.

8. Bias and Validation

8.1 In the spectral region of interest (0.3 to 4.045 µm), the BRITE Monte Carlo computer code has not been adequately verified with experimental data. A comparison of the global irradiance resulting for this code (for example, the hemispherical solar spectral irradiance data for equator-facing plane surfaces at 37° tilt) has been compared with other rigorous codes. The comparison indicates that the various models agree within ~5 % in spectral regions in which there is significant radiation present. Almost all of the differences in the results of these rigorous codes can be traced to differences in the molecular absorption coefficients used as input to the codes.

8.2 Comparison of these reference spectra with clear sky solar spectral irradiance data obtained using various spectroradiometers under AM 1.5 and atmospheric conditions approximating those chosen for modeling these data indicate reasonable agreement.

8.3 The values of direct normal irradiance presented here are the same as those measured with a 5.8° field-of-view normal incidence pyrheliometer, which allows a small amount of circumsolar (diffuse) radiation to be detected. For the type of atmospheric conditions modeled here, this circumsolar radiation adds approximately 1 % to the measured direct irradiance.

APPENDIXES

(Nonmandatory Information)

X1. ATMOSPHERIC PARAMETERS OF THE MODEL ATMOSPHERE

X1.1 The 1962 U.S. Standard Atmosphere Model **(5)** with a rural aerosol was used to produce the data for this standard. This atmospheric model exhibits the following parameters for a vertical path from sea-level to the top of the atmosphere:

Precipitable water vapor	=	14.2 mm
Total ozone	=	3.4 mm or 340 DU (Dobson Units)
Aerosol optical depth at 0.5 µm	=	0.27

X1.2 Atmospheric parameters, such as temperature, pressure, aerosol density, air density, and the density of nine molecular species are defined at 33 levels within the atmosphere. Atmospheric parameters vary exponentially between the 33 levels. The precipitable water vapor and total ozone was derived by integrating water vapor and ozone concentrations throughout the 33 levels. The absorption and scattering properties of the aerosol were calculated with Mie theory. A bimodel, log-normal aerosol size distribution with a complex index of refraction that varies with wavelength was used to define the aerosol. The aerosol optical depth used corresponds to a sea level meteorological optical range of 25 km.

X1.3 The standard data presented here were generated for a solar zenith angle of 48.19°, an air mass of 1.5, and a surface albedo of 0.2. The surface was assumed to have a cosine distribution for reflection or to obey Lambert's law. The atmospheric composition is estimated to be a reasonable average for the 48 contiguous states of the United States over a period of a year. For example, approximately 50 % of the annual energy output at selected U.S. locations is at air mass values greater than AM 1.5 for collector surfaces facing south and tilted at the latitude angle **(12)**.

X2. COMPUTATIONAL TECHNIQUE FOR TABULATED VALUES DERIVED FROM THE SPECTRAL IRRADIANCE

X2.1 *Integrated Irradiance*

X2.1.1 The integrated irradiance values $E_{0-\lambda i}$ presented in Columns 3, 6, and 9, and used in Columns 4, 7, and 10 of Table 1, were computed using a modified trapezoidal integration technique. More specifically:

$$E_{0\rightarrow\lambda_i} = E_{0\rightarrow\lambda_1} + \sum_{j=1}^{i=N-1} \frac{E_{\lambda_{j+1}} + E_{\lambda_j}}{2} \Delta\lambda_j \quad \text{(X2.1)}$$

where:

$$\Delta\lambda_j = \lambda_{j+1-\lambda_j} \quad \text{(X2.2)}$$

and $E_{0-\lambda 1}$ is the contribution before the first tabulated wavelength. This is estimated as half of the first trapezoidal area interval as:

$$E_{0\rightarrow\lambda_1} = \frac{1}{2}\frac{E_{\lambda_1} + E_{\lambda_2}}{2}(\lambda_2 - \lambda_1) \quad \text{(X2.3)}$$

Similarly, $E_{\lambda N}\rightarrow\infty$ the total irradiance beyond the last tabulated wavelength λ_N, is estimated as:

$$E_{\lambda_{N\rightarrow\infty}} = \frac{1}{2}\frac{E_{\lambda_N} + E_{\lambda_{N-1}}}{2}(\lambda_N - \lambda_{N-1}) \quad \text{(X2.4)}$$

Leading to an expression for the solar irradiance:

$$E_{0\rightarrow\infty} = E_{0\rightarrow\lambda_N} + E_{\lambda_{N\rightarrow\infty}} \quad \text{(X2.5)}$$

X2.2 *Selected Ordinates*

X2.2.1 Wavelength values were derived for the selected ordinates by an area interpolation procedure. The *k*th selected ordinate wavelength was derived from:

$$F_k = F_{i+1} - \frac{\Delta F_i}{\Delta\lambda_i}\Delta\lambda_k \quad \text{(X2.6)}$$

where:

$$F_i = \frac{E_{0\rightarrow\lambda_i}}{E_{0\rightarrow\infty}}, \quad \text{(X2.7)}$$

$$\Delta\lambda_k = \lambda_{i+1} - \lambda_k$$

and:

$$F_i < F_k < F_{i+1} \quad \text{(X2.8)}$$

The term λ_k (the wavelength at midpoint of the equal interval) from the following equation:

$$\lambda_k = \lambda_i + \frac{E_{0\rightarrow\lambda_k} - E_{0\rightarrow\lambda_i}}{E_{0\rightarrow\lambda_{i+1}} - E_{0\rightarrow\lambda_i}}(\lambda_{i+1} - \lambda_i) \quad \text{(X2.9)}$$

where:

$$\lambda_i < \lambda_k < \lambda_{i+1} \quad \text{(X2.10)}$$

and:

$$E_{0\rightarrow\lambda_k} = F_{\lambda_k}E_{0\rightarrow\infty} \quad \text{(X2.11)}$$

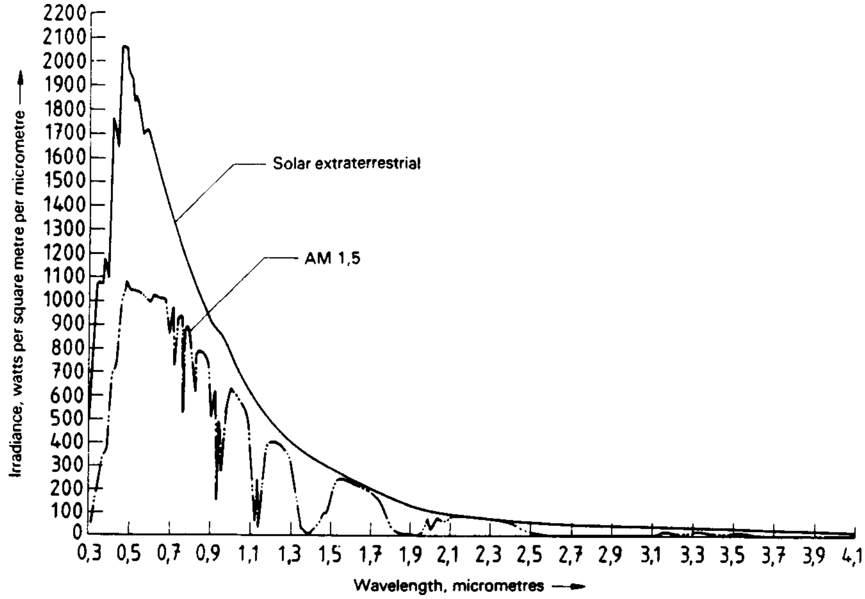
The value of F_k that is appropriate for the *k*th selected ordinate is given by:

$$F_k = \frac{2k-1}{2m} \quad \text{(X2.12)}$$

where m = number of elected ordinate points selected (50 or 100).

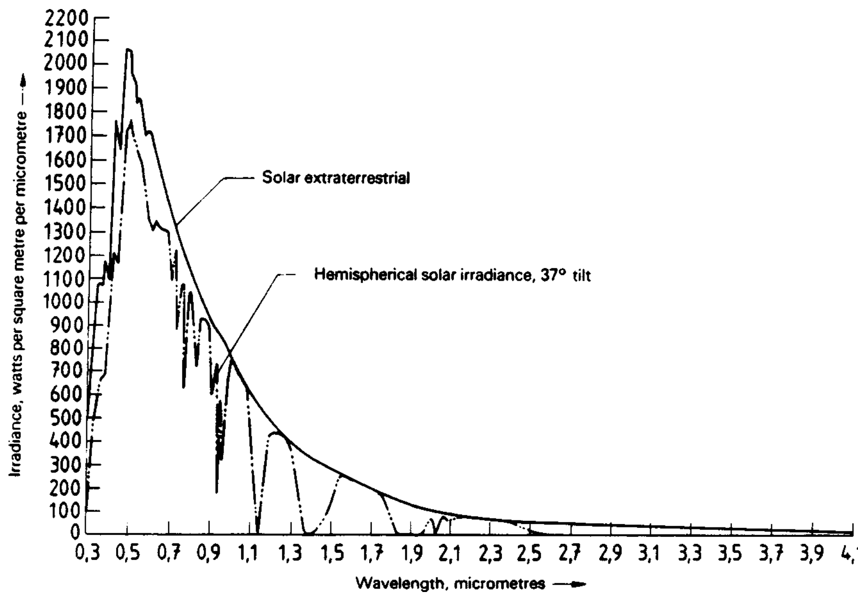
X3. PLOTS OF SOLAR SPECTRAL IRRADIANCE

X3.1 The plot of the AM 1.5 direct normal solar spectral irradiance is presented in Fig. X3.1 and that of the AM 1.5 hemispherical solar spectral irradiance for a 37° tilted plane is presented in Fig. X3.2 Both spectra are for atmospheric conditions defined as the U.S. Standard Atmosphere with a 25-km meteorological optical range, a rural aerosol depth, and an albedo of 0.2.



NOTE 1—U.S. Standard Atmosphere with rural aerosol model (aerosol optical depth at 0.5 µm = 0.27; precipitable water = 14.2 mm; ozone = 3.4 mm; albedo = 0.2; AM = 1.5).

FIG. X3.1 Plot of Direct Normal Irradiance



NOTE 1—U.S. Standard Atmosphere with rural aerosol model (aerosol optical depth at 0.5 µm = 0.27; precipitable water = 14.2 mm; ozone = 3.4 mm; albedo = 0.2; AM = 1.5).

FIG. X3.2 Plot of Hemispherical Solar Irradiance

REFERENCES

(**1**) Fröhlich, C., and Wehrli, C., *Revised Neckel and Labs Extraterrestrial Spectrum*, World Radiation Center, Davos, Switzerland. Personal Communication with R. Bird, Solar Energy Research Institute, Golden, CO, 1981.

(**2**) Neckel, H., and Labs, D., "Improved Data of Solar Spectral Irradiance From 0.33 to 1.25 µm," *Solar Physics*, Vol 74, 1981, pp. 231–249.

(**3**) Bird, R. E., and Hulstrom, R. L., "Application of Monte Carlo Techniques to Insolation Characterization and Prediction," Solar Energy Research Institute, July 1979.

(**4**) Collins, D. G., Blattner, W. G., Wells, M. B., and Horak, H. G., "Backward Monte Carlo Calculations of Polarization Characteristics of the Radiation Emerging from Spherical-Shell Atmospheres," *Applied Optics*, Vol 11, 1972, pp. 2684–2696.

(**5**) McClatchey, R. A., Fenn, R. W., Selby, J. E. A., Volt, F. E., and Garing, J. S., "Optical Properties of the Atmosphere (3rd Ed.)," U.S. Air Force

Cambridge Research Laboratories, AFCRL-72-049 (AD-753-075), Aug. 1972.

(**6**) Shettle, E. P., and Fenn, R. W., "Models of Atmospheric Aerosols and Their Optical Properties," AGARD Conference Proceedings No. 183, *Electromagnetic Wave Propagation Panel Symposium*, Lyngby, Denmark, Oct. 27–31, 1975.

(**7**) Selby, J. E. A., Kneizys, F. X., Chetwynd, J. H., and McClatchey, R. A., "Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 4," U.S. Air Force Geophysics Laboratory, AFGL-TR-78-0053 (AD-A058643), Feb. 28, 1978.

(**8**) Selby, J. E. A., Shettle, E. P., and McClatchey, R. A., "Atmospheric Transmittance From 0.25 to 28.5 µm: Supplement LOWTRAN 3B (1976)," U.S. Air Force Geophysics Laboratory, AFGL-TR-76-0258 (AD-A040701), Nov. 1, 1976.

(**9**) Fröhlich, C., "Photometry and Solar Radiation," Presented at the Annual Meeting of Schweiz. Gesellschaft fur Astrophysik and Astronomie, Nov. 1, 1980.

(**10**) Hardrop, J., "The Sun Among the Stars—III, Solar Distribution of 16 Northern G-Type Stars and Solar Flux Calibration," *Astronomy and Astrophysics*, Vol 91, 1980, pp. 221–232.

(**11**) Fröhlich, C., "Data on Total and Spectral Solar Irradiance: Comments," *Applied Optics*, Vol 22, 1983.

(**12**) Bird, R.E., Hulstrom, R. L., and Lewis, L. J., "Terrestrial Solar Spectral Data Sets," *Solar Energy*, Vol 30, 1983, pp. 563–573.

(**13**) Bird, R.E., Hulstrom, R.L., and Riordan, C., "Spectral Solar Irradiance Data Sets for Selected Terrestrial Conditions," *Solar Cells*, Vol 15, 1985, pp. 365–391.