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RECORDS OF TOTAL SOLAR RADIATION INTENSITY AND THEIR RELATION TO DAYLIGHT INTENSITY [1]

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SYNOPSIS

In this paper an attempt is made to ascertain with what degree of accuracy records of the total radiation, or heat energy, received on a horizontal surface directly from the sun and diffusely from the sky, may be used to determine the intensity of daylight illumination on a horizontal surface. The utility of this investigation is obvious, since continuous records of the total radiation received on a horizontal surface are now obtained by the Weather Bureau at some of its more important stations, and electric-lighting companies are employing methods involving heat energy measurements in determinations of the variability of daylight.

From Abbot's normal solar energy curve, and atmospheric transmission coefficients for different wave lengths of light also due to Abbot, the ordinates have been computed for solar energy curves in atmospheres of different degrees of transparency, and with the sun at different zenith distances.

The ordinates of energy curves for a Planckian distribution at temperatures corresponding to color-temperatures of skylight measured by Priest and others have also been computed, and combined with the ordinates of the solar energy curve to determine the energy distribution in the total radiation received on a horizontal surface. The results indicate that midday radiation is richer in luminous rays than the radiation that is received when the sun is near the horizon.

Comparisons between photometric measurements of daylight and pyrheliometric measurements of the total radiation lead to the same result. They indicate, however, that if the radiation intensity on a horizontal surface, expressed in gram-calories per minute per cm.,[2] is multiplied by 6,700, the result will give the illumination intensity on a horizontal surface in foot-candles within ± 5 per cent, giving values which near noon are too low and which are too high when the sun is near the horizon.

INTRODUCTION

In cooperation with the Illuminating Engineering Society of America, the Weather Bureau has made an extensive study of the intensity of direct sunlight, diffuse skylight, and the total daylight, upon horizontal surfaces, and upon vertical and sloping surfaces differently oriented with respect to the sun.[2]

Recently the Illuminating Engineering Society has asked that methods of daylight recording be considered. The present paper is offered as a contribution to this subject.

RECORDS OF SOLAR RADIATION INTENSITY

Several instruments are now available for obtaining continuous records of solar radiation intensity. One of the best known is the Callendar differential pyrheliometer, in the form of black and bright resistance grids, which when shaded have equal resistances, but when exposed to sunlight show a temperature difference and a resulting difference in resistance. This difference in resistance between the two grids is continuously recorded on a chart by means of a self-adjusting Wheatstone bridge. The excess in the resistance of the black grids over that of the bright grids is nearly proportional to the intensity of the radiation to which the grids are exposed.

Recently thermopiles have been extensively used for recording solar radiation intensities. The Ångström,[3] the Moll,[4] and the Weather Bureau[5] thermoelectric recording pyrheliometers are examples of instruments of this type. The electromotive force generated by the thermopiles, when so exposed that one junction is heated and the other remains at about the temperature of its environment, is nearly proportional to the intensity of the radiation to which they are exposed. The desired temperature difference may be obtained by blackening the receiving surface to which one set of junctions is attached and painting the other white, as in the Weather Bureau instrument, or by painting both sets of junctions black, attaching one set to heavy posts that will conduct away the heat received by radiation, and leaving the other free.

Thermopiles thus prepared are equally sensitive to practically all wave lengths of light found in the solar spectrum. This is not true of the sensitivity of the human eye to sunlight, as is shown by the curved lines of Figure 1.

In this figure, I is a reproduction of Abbot's normal solar energy curve for zero atmosphere.[6] From this curve I have computed Curves II, III, IV, and V, showing the solar energy distribution with average atmospheric transmission for Washington, D. C.,[7] and with solar zenith distances 25°, 60°, 70.7°, and 78.7°, which latter correspond to air masses 1.1, 2.0, 3.0, and 5.0, respectively.

Curve VI gives the Illuminating Engineering Society curve of relative visibility of radiation.[8] We note at once that the maximum of Curve VI falls, with respect to the wave length of light, between the maxima of Curves II and III. That is to say, the wave length of light to which the eye is most sensitive is the wave length of the maximum of the solar energy curve for Washington, with average atmospheric transmission, when the sun is at about zenith distance, 48°, or approximately at noon on March 1 and October 15. Since, however, the atmospheric transmission in the Northern Hemisphere is greater in winter than in summer, and greater in high latitudes than in low latitudes, we may say, in general, that the wave length of light to which the eye is most sensitive is the wave length of the maximum of

[1] Read before section A (cosmical physics subsection), British Association for the Advancement of Science; Toronto, August 11, 1924; and before the Annual Convention of the Illuminating Engineering Society of America, Briarcliff Manor, N. Y., on October 28, 1924. Slight revisions have been made in the text as here printed.

[2] Kimball, Herbert H., and Hand, Irving F., Sky Brightness and Daylight Illumination Measurements. MO. WEATHER REV., September, 1921, 49:481-488; Trans. Illuminating Eng. Soc., Oct. 10, 1921, 16:255-283.
Daylight Illumination on horizontal, vertical, and sloping surfaces. MO. WEATHER REV., December, 1922, 50:615-628; Trans. Illuminating Eng. Soc., May, 1923, 18:434-474.
Kimball, Herbert H., The determination of daylight intensity at a window opening. Trans. Illuminating Eng. Soc., March, 1924, 19:217-234.

[3] Ångström, A., and Dorno, C., Registration of the intensity of sunshine and diffuse sky radiation. MO. WEATHER REV., 1921, 49:135.

[4] Gorczyński, Ladislas, On a simple method of recording the total and partial intensities of solar radiation. MO. WEATHER REV., June, 1924, 52:299-301.

[5] Kimball, Herbert H., and Hobbs, Herman E., A new form of recording thermoelectric pyrheliometer. MO. WEATHER REV., May, 1923, 51:239-242; Jour. Opt. Soc. Amer. & Rev. Sci. Insts., September, 1923, 29:707-718.

[6] Abbot, C. G., Fowle, F. E., and Aldrich, L. B., The distribution of energy in the spectra of the sun and stars. Smithsonian Misc. Coll., vol. 74, No. 7, fig. 1.

[7] Annals of the Astrophysical Observatory of the Smithsonian Institution, 3:135.

[8] Illuminating Eng. Nomenclature and photometric standards. Trans. Ill. Eng. Soc., December, 1918, vol. 13, p. 512.

the solar energy curve at noon in the North Temperate Zone.

In this connection it is of interest to note that the absolute monthly maxima of solar-radiation intensity measured at Washington, D. C., have varied between 1.43 gram-calories per minute per cm.^{2} in January, June, and August, and 1.51 in April and October, or 5.3 per cent. Reduced to mean solar distance, the range of these maxima is from 1.39 gr.-cal. in January to 1.52 in July, or 8.6 per cent.

THE COLOR TEMPERATURE OF DAYLIGHT

The curves of Figure 1 clearly indicate that on a given day, with increase in the zenith distance of the sun, the maximum of the solar energy curve will fall at increasingly longer wave lengths of light, or more and more towards the red end of the spectrum. Priest [9] has measured this variation in terms of color temperature, which he defines as follows: [10]

> The color temperature of a source is the temperature at which a Planckian radiator would emit radiant energy competent to evoke a color of the same quality as that evoked by the radiant energy from the source in question.

In Figure 2, I have plotted against air mass the logarithms of his measured color temperatures of direct sunlight obtained at the Bureau of Standards on February 20, 1920, and have drawn free hand the curve of best fit to his a. m. and p. m. observations.

During the morning of this day pyrheliometric measurements of the solar radiation intensity were made by the Weather Bureau at the American University, only about a mile from the Bureau of Standards. The intensities at air masses 3.0, 2.5, 2.0, and 1.5 were 0.82, 0.91, 1.04, and 1.15, respectively, which are low values for these air masses in February, but not far from the average for the year. Haze was recorded at the time the radiation intensity was measured, and fracto-cumulus clouds commenced to form before noon. The atmospheric transmission coefficient was about 0.78, but varied markedly from time to time.

The logarithms of color temperatures in Figure 2 follow closely a line concave upward, as is usually the case with the logarithms of radiation intensities. The tangents to the curve between air masses 2 and 3, 3 and 4, and 4 and 5, are 0.898, 0.905, and 0.910, respectively.

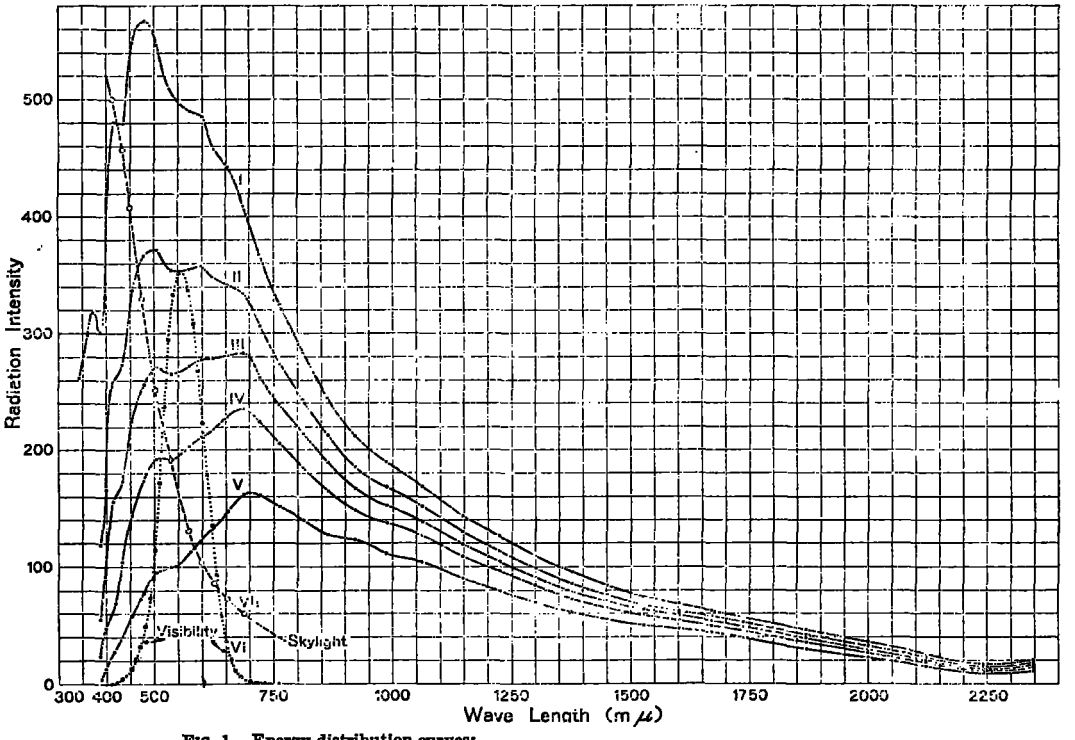

FIG. 1.—Energy distribution curves:
Curve I. Normal solar energy curve outside the atmosphere (m=0).
Curve II. Solar energy curve. Solar zenith distance=25° (m=1.1).
Curve III. Solar energy curve. Solar zenith distance=60° (m=2.0).
Curve IV. Solar energy curve. Solar zenith distance=70.7° (m=3.0).
Curve V. Solar energy curve. Solar zenith distance=78.7° (m=5.0).
Curve VI. Relative visibility of radiation.
Curve VII. Sky light energy curve, Mount Wilson, Calif.

The change in color temperature with air mass is therefore much slower than the change in radiation intensity.

The variation in color temperature is from 1700° K 15 minutes after sunrise, to 5400° K at midday. Extrapolation to zero air mass gives 6500° K. Measurements for June 26, 1922,[11] also plotted in Figure 2, vary between 5300° K 25 minutes after solar noon, and 4510° K at 4:46 p. m., with increasing haziness during the afternoon. The above indicated decrease in the color temperature of direct sunlight with increase in the solar zenith distance shows that we can not expect a constant ratio between radiation intensities and the intensity of direct sunlight. In fact, it has already been shown [12] that the illumination equivalent of 1 gr. cal./min./cm.^{2} varies between 7,040 foot-candles with solar zenith distance 20°, and 6,320 foot-candles with solar zenith distance 79.8°.

[9] Priest, Irwin G., A new study of the Leucoscope and its application to pyrometry. VI. Experiments on Leucoscopic determination of the quality of sunlight and its diurnal variation. Jour. Optical Soc. of Amer. 4:480-484.

[10] Priest, Irwin G., The Colorimetry and Photometry of Daylight and Incandescent Illuminants. Jour. Opt. Soc. Amer. & Rev. Sci. Inst. 7, p. 1180, December, 1923.

[11] Jour. Opt. Soc. Amer. and Review of Scientific Instruments, 1923, 7: 78.

[12] Kimball, Herbert H. and Hand, Irving F., Daylight Illumination on Horizontal, Vertical, and Sloping Surfaces. MO. WEATHER REV., 1922, 50: 622, Table 6.

THE QUALITY OF DAYLIGHT

We are interested not so much in the color temperature of direct sunlight, however, as in the quality of the total daylight, which is made up partly of direct sunlight and partly of diffuse light from the sky. Table 1 shows the ratio of direct solar radiation to diffuse sky radiation as measured on a horizontally exposed surface at various places and by different observers. At Washington, D. C., the measurements were made with the thermoelectric pyrheliometer; at Madison, Wis., and Lincoln, Nebr., with the Callendar recording pyrheliometer.[13] The measurements at Flint Island, and Mount Wilson and Mount Whitney, Calif., were made by the Smithsonian Institution with the bolometer.[14] Those at Hump Mountain, N. C., were made by the Smithsonian Institution[15] with the pyranometer, and do not seem to be in accord with the other measurements, since they show too little sky radiation.

It will be seen that the ratios of Table 1 increase with height above sea level, and decrease as the solar zenith distance increases. With the sun within a few degrees of the horizon more radiation may be received on a horizontal surface diffusely from the sky than directly from the sun. The Washington ratios show a marked seasonal variation, having a maximum in winter and a minimum in summer.

TABLE 1.—*Ratio of direct solar radiation received on a horizontal surface to diffuse sky radiation*

	Solar zenith distance												
	7.5°	25°	30°	48.3°	55°	60°	66.5°	70.7°	73.6°	75.7°	77.4°	78.7°	85.0°
Washington, D.C.:													
Winter	----	----	----	7.02	----	5.18	4.02	3.36	2.97	2.48	2.11	1.70	----
Spring	----	8.72	----	6.53	----	4.87	3.91	3.10	2.56	2.14	1.83	1.53	----
Summer	----	4.25	----	3.76	----	3.18	2.72	2.25	1.96	1.71	1.64	1.50	----
Mean of all	----	5.31	----	4.81	----	4.12	3.41	2.79	2.39	2.05	1.81	1.60	----
Lincoln, Nebr.	----	5.67	----	5.25	----	4.26	3.76	3.17	2.70	2.33	2.03	1.86	----
Madison, Wis.	----	5.25	----	5.25	----	3.17	3.00	2.85	1.94	1.78	----	----	----
Flint Island	----	[1] 4.17	----	----	----	----	----	----	----	----	----	----	----
Hump Mountain	----	----	----	11.00	----	8.97	7.19	6.78	5.52	5.33	4.69	4.13	----
Mount Whitney	----	12.25	----	----	----	----	----	----	----	----	----	----	----
Mount Wilson	6.27	[2] 6.10	6.00	5.08	4.13	[2] 3.90	3.23	[2] 2.70	----	2.12	----	[2] 1.62	0.82

[1] Solar zenith distance=18.6°. [2] Interpolated values.

Abbot has determined the energy curve for skylight on Mount Wilson,[16] and it is reproduced as Curve VII of Figure 1. It shows the excess of radiation of short wave length in diffuse radiation from the sky as compared with direct solar radiation.

Priest [17] and some others have also measured the color temperature of skylight, and have found it to vary when no clouds are present from about 6000° K to 24000° K. With thin clouds the color temperature sometimes dropped below 7000° K and with a uniformly overcast sky to 6300° K.

Knowing the color temperature of radiation, we may reproduce approximately its spectrum energy curve, and knowing the ratio between the intensity of direct solar and diffuse sky radiation we may express the energy of both for different wave lengths in the same units.

Abbot's energy curve for sky light at Mount Wilson approximates the Planckian energy distribution [18] for a temperature of slightly over 50000° K. This seems high, but Priest obtained a color temperature for sky light at Washington on the morning of November 30 and near noon December 28, 1921, of 24150° K. It is well known that the average sky at Mount Wilson is much bluer than is even the clearest sky at Washington. On November 30, 1921, the solar radiation intensity at Washington with the sun 11.3° above the horizon, corresponding to air mass 5.0, was 0.69 gr. cal, as compared with a normal at this air mass for November of 0.76. On December 28, 1921, at noon, solar radiation intensities were nearly 6 per cent above the normal for this hour in December. The polarization of sky light was 65 per cent as compared with an average for December of 59 per cent.

In general, however, the color temperature of sky light during the summer months, in the absence of clouds, appears to have varied between 8000° and 15000° K. Measurements on June 30, 1922, a hazy day with solar radiation intensities much below the average for June, give sky light color temperatures of from 8080° to 9950° K.

Abbot's bolometric measurements at Washington were made only on days with exceptionally clear skies. Curves

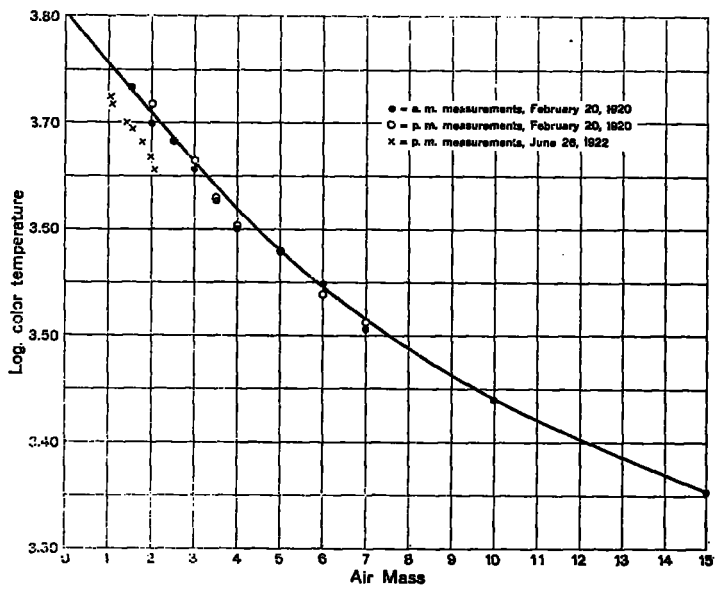

FIG. 2.—Color temperature of direct sunlight

II to V, Figure 1, therefore, represent the mean solar energy distribution for exceptionally clear days throughout the year.

In Table 2 (b) there is given in the line headed "Sun, Z=25°, Z=60°," etc., the intensity of solar radiation at selected wave lengths in the visible spectrum, obtained from Curves II, III, IV, and V, Figure 1, by multiplying the ordinates of these curves at the selected wave lengths by the cosines of the solar zenith distances for which the respective curves have been computed.

By a similar process the vertical components of solar radiation intensity have been computed for May 14, 1907, at Washington, a day with a hazy sky, for February 15, 1907, at Washington, an unusually clear day, and for an average day at Mount Wilson, Calif. (See Table 2 (a), (c), and (d).)

[13] MO. WEATHER REV., August, 1914, 42: 474-489: 1924, 52: 42.
[14] Annals of the Astrophysical Observatory, 3: 141-151.
[15] Moore, A. F. and Abbot, L. H., The Brightness of the Sky. Smithsonian Misc. Coll., vol. 71, No. 4.
[16] Annals of the Astrophysical Observatory, 2: 155.
[17] Jour. Opt. Soc. Amer., 1920, 4: 483; 1923, 7: 78, 1184.

[18] Distribution according to Planck's formula:

$$E=c_1\lambda^{-5}\left(\frac{c_2}{e^{\lambda T}-1}\right)^{-1} \text{ in which } c_2=14{,}350 \text{ micron-degrees.}$$

The value of c_1 does not affect the distribution.

TABLE 2.—*Energy distribution in the visible spectrum of sunlight and sky light, as received on a horizontal surface, with the sun at different zenith distances, Z*

WAVE LENGTH, $m\mu$

	397	413	431	452	475	503	535	556	574	591	624	653	686	720	764
(a) WASHINGTON, D. C., MAY 14, 1907—SKY HAZY															
Sun, Z=25°	101	205	226	254	292	300	288	303	296	302	296	289	279	257	230
Sky	135	127	117	109	99	90	81	72	68	63	56	49	44	38	32
Total	236	332	343	363	391	390	369	375	364	365	352	338	323	295	262
Total, adjusted	126	177	183	194	208	208	197	200	194	195	188	180	177	157	140
(Curve of about 6000° K)															
Sun, Z=60°	22.0	60.0	73.0	80.5	100	110	108	122	117	122	124	124	122	114	104
Sky	78.7	74.7	68.8	63.7	58	53	47	42	40	37	33	29	26	22	19
Total	101	135	142	144	158	163	155	164	157	159	157	153	148	136	123
Total, adjusted	123	165	173	176	193	199	189	200	192	194	192	187	181	166	150
(Curve of about 6000° K)															
Sun, Z=70.7°	5.3	19.9	26.5	28.8	40.1	46.0	47.0	56.3	53.6	56.9	59.9	62.2	61.9	59.6	54.9
Sky	58.8	55.8	51.4	47.6	43.5	39.4	35.3	31.5	30.0	27.8	24.6	21.8	19.2	16.7	14.2
Total	64.1	75.7	77.9	76.4	83.6	85.4	82.3	87.8	83.6	84.7	84.5	84.0	81.1	76.3	69.1
Total, adjusted	146	172	177	174	190	195	188	200	190	193	193	191	185	174	157
(Curve of about 6000° K)															
Sun, Z=78.7°	0.4	2.9	4.7	4.9	8.4	11.0	12.0	16.5	15.3	17.1	19.2	21.2	21.8	22.1	21.0
Sky	34.5	32.8	30.2	28.0	25.6	23.2	20.7	18.5	17.6	16.3	14.4	12.8	11.3	9.8	8.3
Total	34.9	35.7	34.9	32.9	34.0	34.2	32.7	35.0	32.9	33.4	33.6	34.0	33.1	31.9	29.3
Total, adjusted	199	204	199	188	194	195	187	200	188	191	192	194	189	182	167
(Curve of between 5000° and 6000° K)															
(b) WASHINGTON, D. C., AVERAGE CLOUDLESS SKY															
Sun, Z=25°	151	235	249	305	333	338	322	322	322	325	316	310	304	277	248
Sky	135	125	113	97	84	73	62	53	49	46	38	33	27	25	20
Total	286	360	362	402	417	411	384	375	371	371	354	343	331	302	268
Total, adjusted	153	192	193	214	222	220	204	200	198	198	189	183	177	161	143
(Curve of about 6000° K)															
Sun, Z=60°	46.0	78.0	86.5	112	128	136	132	134	136	139	140	140	142	131	119
Sky	80.3	74.1	66.9	58	50	43	37	31	29	27	22	20	16	15	12
Total	126	152	153	170	178	179	169	165	165	166	162	160	158	146	131
Total, adjusted	153	185	186	206	216	217	205	200	200	201	202	194	192	177	159
(Curve of about 6000° K)															
Sun, Z=70.7°	15.9	29.5	34.4	47.7	57.3	63.2	63.2	65.5	67.2	69.8	72.2	75.5	77.8	73.8	67.9
Sky	64.7	59.7	53.9	46.6	40.3	34.8	29.7	25.2	23.4	21.9	18.1	15.9	13.1	11.8	9.8
Total	80.6	89.2	88.3	94.3	97.6	98.0	92.9	90.7	90.6	91.7	90.3	91.4	90.9	85.6	77.7
Total, adjusted	158	197	195	208	215	221	205	200	200	202	199	202	200	189	171
(Curve of about 6000° K)															
Sun, Z=78.7	2.6	5.7	7.4	11.6	15.3	18.6	19.6	20.8	22.1	23.7	26.1	29.0	31.8	31.4	29.6
Sky	50.9	46.9	42.4	36.6	31.7	27.3	23.4	19.8	18.4	17.2	14.3	12.5	10.3	9.3	7.7
Total	53.5	52.6	49.8	48.2	47.0	45.9	43.0	40.6	40.5	40.9	40.4	41.5	42.1	40.7	37.3
Total, adjusted	264	259	245	237	232	226	212	200	200	201	199	204	208	200	184
(Curve of about 7000° K)															
(c) WASHINGTON, D. C., FEBRUARY 15, 1907															
Sun, Z=60°	92.5	130	130	162	198	192	176	176	176	182	175	176	166	151	138
Sky	74.8	77	59	50	42	35	28	26	23	20	18	15	13	11	9
Total	167	207	189	212	240	227	204	202	199	202	193	191	179	162	147
Total, adjusted	165	205	187	210	238	225	202	200	197	200	191	189	177	160	146
(Curve of about 7000° K)															
Sun, Z=70.7°	45.7	63.6	62.9	82.8	109	106	97.0	98.3	99.0	105	101	106	99.3	91.0	83.7
Sky	68.7	62.3	54.5	46.5	38	32	25.8	23.7	20.9	18	16	14	11.6	10.0	8.3
Total	114	126	117	129	147	138	123	122	120	123	117	120	111	101	92
Total, adjusted	187	207	192	211	241	226	202	200	197	202	192	197	182	166	151
(Curve of about 7000° K)															
Sun, Z=78.7°	15.3	20.4	20.2	29.2	45.1	43.9	40.0	41.4	42.3	46.8	45.9	51.0	47.8	44.5	42.1
Sky	65.6	59.5	52.1	44.4	36.7	30.6	24.7	22.6	20.0	17.7	15.4	13.1	11.1	9.5	8.1
Total	80.9	79.9	72.3	73.6	81.8	74.5	64.7	64.0	62.3	64.5	61.3	64.1	58.9	54.0	50.2
Total, adjusted	253	250	226	230	256	233	202	200	195	202	192	200	184	169	157
(Curve of about 7000° K+)															

TABLE 2.—*Energy distribution in the visible spectrum of sunlight and sky light, as received on a horizontal surface, with the sun at different zenith distances, Z*—Continued

WAVE LENGTH, $m\mu$—Continued

(*d*) MOUNT WILSON, AVERAGE CLOUDLESS SKY

	397	413	431	452	475	503	535	556	574	591	624	653	686	720	764
Sun, Z=25°	217	314	333	396	425	424	401	393	389	393	375	363	345	317	282
Sky	73	60	53	44	37	30	24	22	18	17	14	11	9	8	6
Total	290	374	386	440	462	454	425	415	407	410	389	374	354	325	288
Total, adjusted	140	181	186	212	223	219	205	200	197	198	187	180	171	157	139
(Curve of about 6000° K+)															
Sun, Z=60°	89.5	132	148	180	200	204	197	194	192	196	190	188	182	168	150
Sky	58.5	48	43	35	30	24	20	18	15	13	11	9	7	6	5
Total	148	180	191	215	230	228	217	212	207	209	201	197	189	174	155
Total, adjusted	140	170	180	203	217	215	205	200	196	198	190	186	179	175	147
(Curve of about 6000° K+)															
Sun, Z=70.7°	43.0	64.5	76.4	97.0	112	117	115	113	113	117	115	116	113	106	96.0
Sky	50.5	41.6	36.5	30.4	25	21	17	15	13	12	9	7	6	5	4.6
Total	93.5	106	113	127	137	138	132	128	126	129	124	123	119	111	101
Total, adjusted	146	166	177	199	214	216	206	200	197	202	194	192	186	173	158
(Curve of about 6000° K+)															
Sun, Z=78.7	13.5	21.0	27.8	37.8	46.6	51.7	52.9	52.5	52.5	56.1	56.4	59.4	59.4	57.6	52.9
Sky	45.8	37.7	33.1	27.5	22.9	19.0	15.3	13.7	11.6	10.4	8.6	6.7	5.6	4.9	4.2
Total	59.3	58.7	60.9	65.3	69.5	70.7	68.2	66.2	64.1	66.5	65.0	66.1	65.0	62.5	57.1
Total, adjusted	179	177	184	197	210	214	206	200	194	201	196	200	196	187	173
(Curve of about 6000° K+)															

In Table 2, in the lines headed "Sky," there is given the intensity of sky radiation for the same selected wave lengths as for solar radiation, computed as follows: For May, 1907, the energy distribution has been assumed to correspond to a Planckian energy distribution [19] for a temperature of 10000° K; for average clear skies at Washington, to 16000° K; for February 15, 1907, to 24000° K; for Mount Wilson, 50000° K. The intensity relative to solar radiation intensity has been obtained as follows:

Let A = area under solar energy curves (such as Curves II, III, IV, and V, Figure 1) where the energy is expressed in arbitrary units. Allowance must be made for depletion by water-vapor absorption in the infra-red, and for radiations of both shorter and longer wave lengths than are included under the curves.

Let a' = area under the energy curve for a Planckian energy distribution at the assumed color temperature of sky light, with the energy expressed in arbitrary units, but with the wave-length scale the same as for A. Here, also, allowance must be made for the fading out of the solar spectrum for wave lengths shorter than 350 $m\mu$. It has been assumed that the spectrum of daylight ends, like the solar spectrum, at 290 $m\mu$.

Let R = the ratios between the intensity of solar and sky radiation as given in Table 1.

Let a = the area of a' expressed in the same units as A.

Then $a = A/R$, and to reduce the ordinates of the energy distribution at the assumed color temperature of sky light to the same scale as the ordinates of the solar energy curves, we must multiply them by the ratio a/a'.

The sum of the ordinates for solar and sky energy curves thus obtained gives the intensity of the total radiation at the different wave lengths. For ease of comparison these totals have been adjusted so as to give a value of 200 at wave length 556 $m\mu$. Following these adjusted values, I have indicated the temperature of the

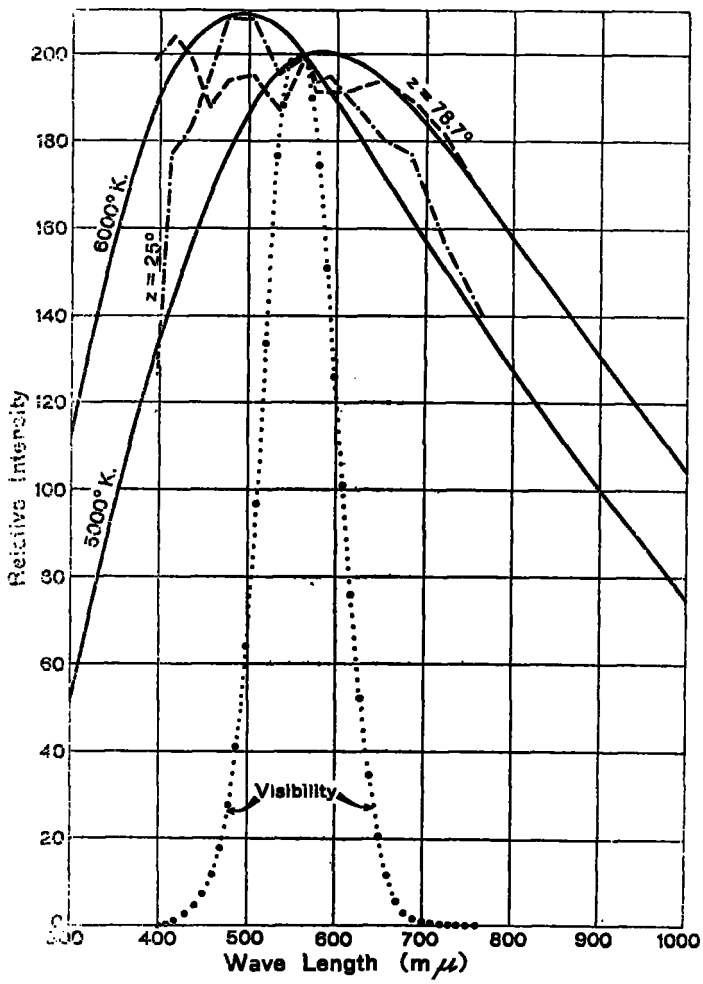

FIG. 3.—Energy distribution curves: According to Planck's equation, for temperatures of 5000° K and 6000° K, respectively; for the total solar and sky radiation with the sun at zenith distances, Z, of 25° and 78.7°, respectively, and for the relative visibility radiation

[19] "Tables and graphs for facilitating computations of spectral energy distribution," by Frehafer and Snow, Bureau of Standards Misc. Publication No. 56, have been utilized in determining the distribution for temperatures below 28000° K.

Planckian energy distribution to which they most nearly correspond. As we would expect, the correspondence is only approximate.

In Figure 3 are reproduced the Planckian energy distribution curves for temperatures of 5000° K and 6000° K,[20] and also the computed curves for the total solar and sky radiation on May 14, 1907, at Washington, for zenith distances of the sun of 25° and 78.7°, respectively. Comparing these two latter curves with the curve of relative visibility, we are led to the conclusion that the radiation at noon on this day was richer, proportionately, in visible radiation than was the radiation with the sun 11.3° above the horizon, or at about 6 p. m., apparent time.

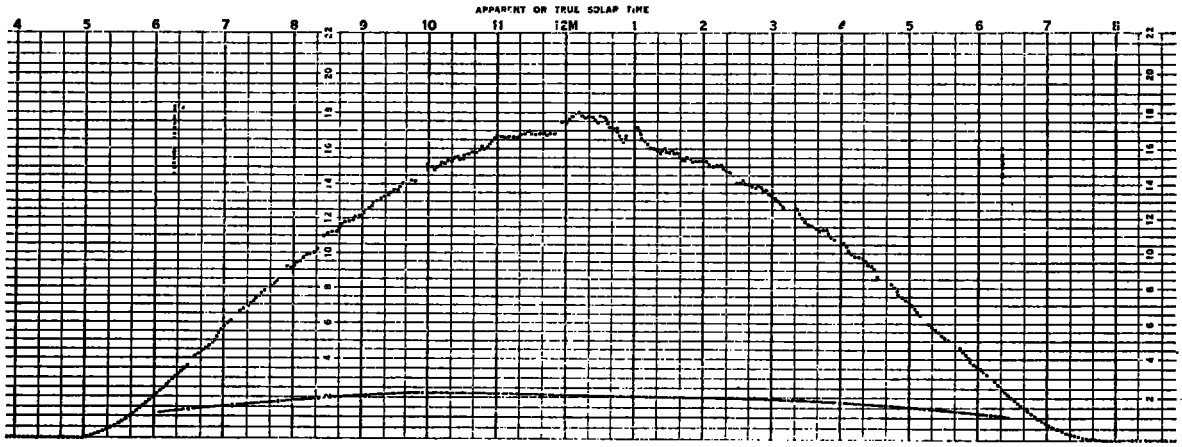

FIG. 4.—Record of the total solar radiation received on a horizontal surface at Washington, D. C., on July 11, 1924

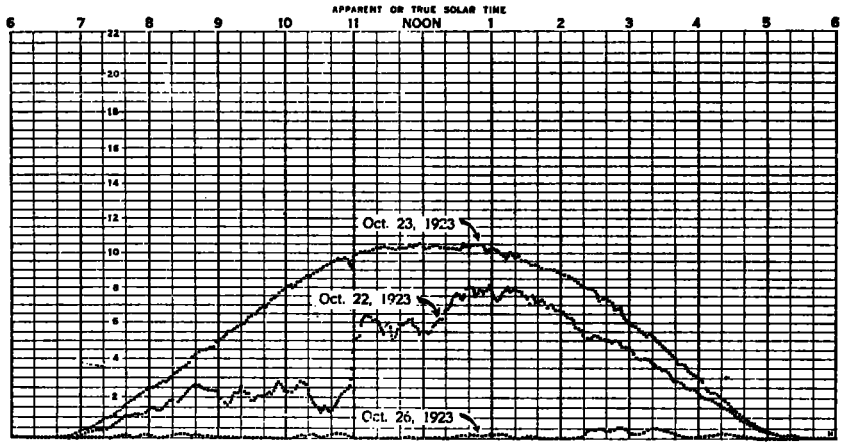

FIG. 5.—Records of the total solar radiation received on a horizontal surface at the University Observatory, Chicago, Ill.

COMPARISONS OF PHOTOMETRIC MEASUREMENTS OF DAYLIGHT AND PYRHELIOMETRIC MEASUREMENTS OF SOLAR RADIATION INTENSITY

During the late spring and the summer months of the present year frequent comparisons have been made between daylight intensity measurements made by a Sharp-Millar photometer and the intensity of the total solar and sky radiation as recorded by a thermoelectric pyrheliometer. The latter instrument was installed on the roof of the College of History Building, American University, D. C., and the photometer was read on the roof of the same building. The receiving surfaces of both instruments were exposed horizontally. Table 3 summarizes the comparisons between the readings of the two instruments. It also contains a summary of previous comparisons between solar radiation intensity at normal incidence and the corresponding illumination intensity.

Like Figure 3, Table 3 shows that the total radiation received on a horizontal surface is not quite so rich in luminous radiation with low sun as with high sun. This is also the case with direct solar radiation. In fact, when we consider the difficulties of obtaining accurate measurements of daylight illumination and the comparatively few measurements included in this research (about 10 for each air mass greater than 2.0, 26 for air mass 1.5, and 16 for air mass 1.1), we must conclude that the differences found between the illumination equivalent of direct solar radiation and the total radiation are of little significance, although the equivalent for the total radiation is consistently smaller, as we would expect.

[20] This curve fits closely Abbot's normal solar energy curve. (See fig. 1, Curve I.)

TABLE 3.—*Illumination equivalent of a gram-calory per minute per square centimeter of radiation with the sun at different zenith distances*

Air mass / Solar zenith distance	1.1 / 25°	1.5 / 47.3°	2.0 / 60.0°	2.5 / 67.6°	3.0 / 70.7°	3.5 / 73.6°	4.0 / 75.7°	4.5 / 77.4°	5.0 / 78.7°
Direct solar radiation	F. C. 7020	F. C. 6880	F. C. 6740	F. C. 6650	F. C. 6580	F. C. 6520	F. C. 6460	F. C. 6410	F. C. 6370
Total radiation on a horizontal surface	7000	6740	6470	6320	6260	6220	6200	6200	6200

Figure 4 is a copy of the record made by the pyrheliometer on July 11, 1924. The upper trace is a record of the total (direct solar + diffuse sky) radiation received on a horizontal surface. The lower curve is drawn through records of sky radiation only, obtained by shading the pyrheliometer from direct sunlight. Vertical rows of dots were made on the record sheet at 6 a. m. and 6 p. m., apparent time, or about 6:13 a. m. and p. m., 75th meridian time. They show that the register clock was faster than apparent time, and gaining.

In figure 5 are reproduced three record traces made at the Weather Bureau Observatory, University of Chicago, in October, 1923. October 23 was a cloudless day, with a moderate northeast wind from off Lake Michigan, about a mile distant, which blew away the city smoke. October 22 was also a cloudness day, but with a light wind from the northwest in the morning. The station records state that "Dense city smoke prevailed until 10:30 a. m. (10:51 apparent time), when it was swept away by the wind shifting to the northeast. Standing objects not visible much in excess of one-eighth of a mile." Between 10 a. m. and 11 a. m., when the depression in the record is greatest, the radiation intensity averaged 24 per cent as great as during the same hour on the 23d.

On October 26, the observer's notes read: "Dense city smoke during forenoon. Sky overcast with clouds. Light rain after 2:43 p. m."

As we would expect, comparisons of individual series of photometric readings with the pyrheliometric record show large departures from the mean results given in Table 3. Thus, from the photometric readings made at about 7:48, 8:31, 9:51, and 11:48 a. m., July 11, 1924, we obtain for the ratio

$$\frac{\text{Illumination intensity (F. C.)}}{\text{Radiation intensity (gr.-cal./min.cm.}^2\text{)}}$$

the values 6320, 5920, 6400, and 7460, respectively; and at 10:08 a. m., 12:09 p. m., and 1:58 p. m., July 18, 1924, the ratios 7850, 6580, and 7140, respectively. It is believed that these variations are to be attributed principally to inaccuracies in the photometric readings rather than to inaccuracies in the pyrheliometric record. The sky was somewhat clearer on July 18 than on July 11.

A comparison between the illumination and the radiation intensities of sky light made at Washington, D. C., in summer, indicate that it is relatively richer in luminous radiation than is direct sunlight, and especially with low sun. This is hardly what we would expect from a comparison, in Figure 1, of Curve VII, for sky light, and Curves II, III, IV, and V, for sunlight, with Curve VI. It must be remembered, however, that a summer sky in Washington has a much lower color temperature, and, in consequence, radiates relatively less of the ultra-violet than is indicated by Curve VII. Therefore, the ratios as found may be correct; but in comparisons of skylight intensity we must take into account a large probable error in both the pyrheliometric and the photometer readings.

When dense clouds cover the sky so that the radiation intensity is perhaps even less than that from a clear sky the ratio of illumination intensity to radiation intensity is likewise abnormally high. The mean of 13 series of comparisons between illumination and radiation intensities with a completely overcast sky gives for the above ratio the value 7440.

Curve VII in Figure 1 indicates that for clear sky the ratio

$$\frac{\text{Illumination intensity}}{\text{Radiation intensity}}$$

should be lower than for direct solar radiation. Priest's color temperatures of sky light, already referred to, give a like indication, although with cloudy skies the difference is small.

CONCLUSIONS

With cloudless skies the illumination equivalents of Table 3 when applied to radiation intensities should give daylight intensities with an accuracy comparable to that of ordinary photometric readings. The factor 6700 will, on an average, give the daylight intensity within ± 5 per cent, giving too low intensities near noon in summer and too high intensities when the sun is near the horizon.

With the sky covered with clouds the factor averages higher, probably not far from 7,000.

551.578.1 : 551.506

APPLICATION OF SCHUSTER'S PERIODOGRAM TO LONG RAINFALL RECORDS, BEGINNING 1748

By DINSMORE ALTER

(University of Kansas, Nov., 1924)

The present paper is an extension of work on rainfall periodicities carried on during the past four years(1). In the previous papers a single short periodicity was investigated. In the present paper the investigation is carried to longer periods to which a much more general method of analysis must be applied.

Of the various methods that have been proposed in the search for hidden periodicities, that formulated by Schuster (2) and used by him in a search for periods in the Greenwich magnetic data, seems the most practical for application to this problem.

Schuster's method consists, first, of passing sine curves, of arbitrarily selected periods, through the data in such manner as best to represent them by each. These periods must be so closely chosen that there shall be no intermediate ones untried that can have a large final disagreement in phase from the next neighboring one chosen for examination. The second part of the method consists of plotting the intensities of these curves as ordinates of another curve whose abscissae are the periods so chosen. This last curve he calls the periodogram.

The method of obtaining these sine curves is as follows: Suppose a period to be tried of length equal to n times the time interval α between successive observations. The first n data values are then written as a row, each heading a column. The next n values then form the second row of these n columns, etc, until all p observations have been used or, as is often done, until there are not enough data left to form another complete row. In the first case the average value of each column is taken, in the second the sum may be used instead. The first case has a slight theoretical disadvantage in that columns of slightly different weight are considered as being of equal weight. Schuster used the second alternative, although it involves the neglect of considerable data