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THE DISCREPANCY BETWEEN SOLAR RADIATION MEASURES BY THE ACTINOMETER AND BY THE SPECTRO-BOLOMETER

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(Communicated by S. P. Langley, Secretary of the Smithsonian Institution.)

The object of this paper is to show, that by means of actinometric observations alone, of the intensity of the total solar radiation received at the surface of the earth, we may, by the application of a certain correction, determine the radiation outside the atmosphere with the same degree of accuracy which is reached in a bolographic determination made in Washington by the observation of homogeneous rays.

Mr. Langley demonstrated[1] many years ago that the use of Bouguer's formula with ordinary actinometric observations necessarily leads to too low a value of the solar radiation outside of our atmosphere. This formula may be written $E_x = E_0 a^{m_x}$ where E_x and E_0 are the actinometric readings in radiation units at the air-masses m_x and zero respectively, and "a" the coefficient of transmission of our atmosphere for unit air-mass. The unit air-mass is such that, with the sun in the zenith, the radiation passes through one air-mass or atmosphere to the observer at the surface of the earth.

In employing the formula to compute E_0 from actinometer measures, the error arises from the assumption that the coefficient of transmission "a" is the same for all wavelengths, whereas at Washington the general transmission coefficients may vary from 0.39 to 0.97 (and in water vapor bands may even reach zero), between the wavelengths $0^{\mu}.4$ to $2^{\mu}.0$; beyond these limiting wavelengths the amount of solar radiation is negligible.

[1] *American Journal of Science* (3), XXVIII, p. 163, 1884.

In a paper published by Mr. Langley in the *Astrophysical Journal*,[1] a possible change in the value of the solar radiation was surmised. This possibility is indicated by several kinds of circumstantial evidence:

1. By the spectro-bolographic[2] determinations of the solar radiation by the study of homogeneous rays, thus avoiding the erroneous assumption of uniform atmospheric transmission coefficients for all wavelengths.

2.[3] In several cases by apparent changes in the value of the transmissibility of the solar atmosphere, indicating some change in solar condition coincident with the observed changes in the radiation values determined as just mentioned.

And 3. By observed changes in terrestrial temperature as noted over the greater portion of the northern hemisphere of our earth.

If such changes in the solar radiation actually do take place, then their detection and measurement by some easy and rapid method is of great importance, since the solar radiation is one of the most important factors in determining meteorological phenomena. The bolographic method just mentioned involves not only the use of costly and extremely delicate apparatus requiring two skilled observers, but the subsequent reductions are so laborious that a single reduction requires at least a week's time. The second method, though leading to results with much less time-consuming reductions, yet involves still more costly and quite as delicate apparatus. Hence if some trustworthy method could be determined for computing the so-called solar constant from ordinary actinometric measures, the desired values of the solar radiation could then be obtained not only quickly but cheaply. A secondary actinometer costing probably only $10 or $15 would be good enough for such measures, and indeed as good as any, since all actinometers at present in use must be considered as secondary instruments.

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[1] *Astrophysical Journal*, XIX, p. 305, 1904.

[2] A full description of the spectro-bolometric determinations may be found in the SMITHSONIAN MISCELLANEOUS COLLECTIONS, Quarterly Issue, Volume I, page 74, 1903. Briefly, solar energy curves are taken at frequent intervals during an afternoon. These serve for the determination of Bouguer's "*a*"s for each wavelength. After an energy curve has been corrected for all instrumental absorptions, it is then, by means of these atmospheric transmission coefficients, corrected to its value outside the atmosphere. The ratio of this final area to that before this last correction, multiplied by the simultaneous actinometer reading, gives the so-called spectro-bolographic determination of the extra-atmospheric solar radiation. This is then reduced to the mean solar distance.

[3] *Nature*, vol. 70, p. 198, 1904.

Actinometric measures, indeed, in common with the bolometric process, depend on the estimation of the transmission of the earth's atmosphere and are at a great disadvantage as compared with the process of observation of the absorption of the solar envelope originally devised by Mr. Langley where, as seems very possible from the solar studies now being carried on here, the changes in the effective emission of the sun itself are determined. In the latter process less than three minutes of constant conditions in our atmosphere are required to make an observation of the apparent absorption of the solar envelope. The actinometric and bolographic processes, on the other hand, demand two or three hour's constant condition of atmospheric transmissibility, which occurs comparatively seldom in such a locality as Washington.

The observations discussed in this paper were made with two actinometers. One was of the Crova pattern, a glass and mercury thermometer, the blackened bulb of which was situated in the center of a metallic sphere, polished nickel without, blackened within, and having an opening allowing a beam of sunlight of slightly less diameter than the bulb to fall on the latter. The other actinometer was home-made and consisted of a thin flat cylindrical copper receptacle filled with mercury, blackened over the exposed end with platinum black, and the rest nickeled and surrounded by a wooden sphere, bright within, having the beam similarly limited by diaphragms. A mercury thermometer inserted in the copper vessel served to indicate the rise in temperature. Observations are made in the same manner with both actinometers. By cutting the sunlight off from the aperture, a cooling correction is determined for two minutes; the instrument is then exposed to the solar radiation for two minutes, and a final cooling correction for two minutes completes the observation. The radiation value is obtained from the rate of rise during exposure, corrected by the mean of the cooling corrections determined before and after the exposure to the sun. Values of the solar constant have been computed by Bouguer's formula from actinometric measures alone, to see how far short they fall from the spectro-bolometric determinations from the same data.

In this discussion of actinometric measures the observations will accordingly first be treated as if they followed the formula $E_x = E_0 a^{m_x}$ which is better adapted to the purpose in the linear form

$$\log E_x = \log E_0 + m_x \log a$$

where $\log E_x$ and m_x are employed as variables. Thus in order to get a value of the solar radiation at least partly corrected for the absorption in the earth's atmosphere, the observations are plotted with air-masses as abscissæ, and logarithms of the radiation measures as ordinates.

Now the range of air-masses is such that the points thus plotted are very nearly linear, although a slight curvature convex towards

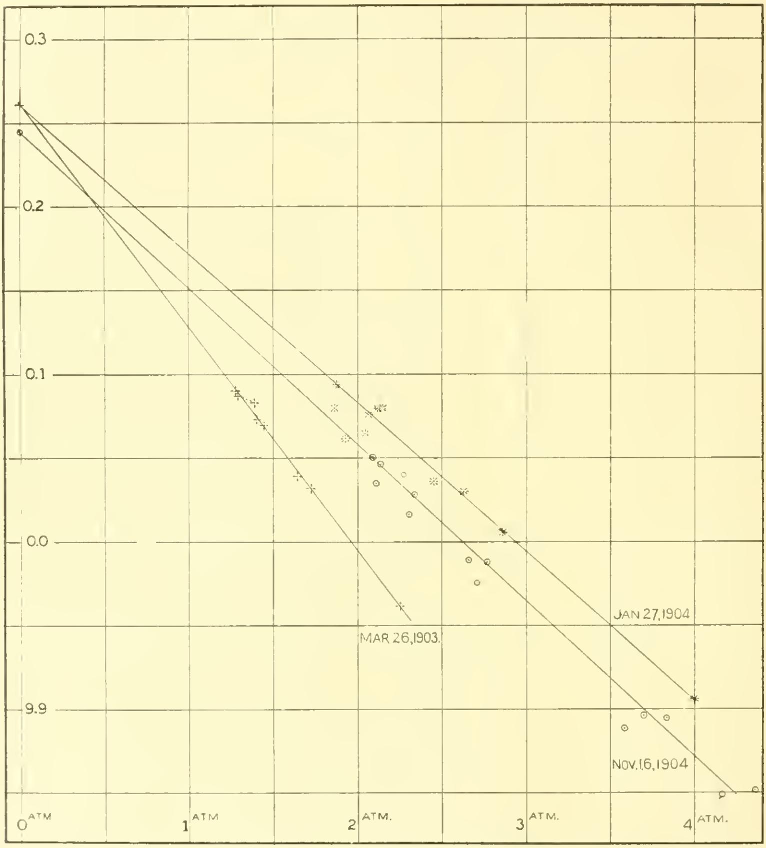

FIG. 62.—Bonguer's Formula and Actinometry of Solar Radiation. Abscissæ are air-masses. Ordinates are logarithms of actinometer measures.

the axis of abscissæ might be expected in accordance with what Mr. Langley has shown, and is indeed at times noticeable where the range of air-masses is great. The straight line best representing these points is then drawn and its intersection with the axis of ordinates ($m = 0$) gives a preliminary too low value of the extrapolated solar radiation.

This process as applied to three different days may be seen in figure 62. The deviations of the observation from the straight line used in the extrapolation are given in Table I and serve as an indication both of the accuracy of the observations and the suitability of the straight line for representing the points.

TABLE I

Logarithmic deviations.

	Mar. 26, 1903.	Jan. 27, 1904.	Nov. 16, 1904.
	0.000	+.002	+.014
	0.000	—.001	—.006
	—0.003	+.003	+.007
	+0.001	—.007	—.003
	—0.002	+.010	—.011
	+0.0007	+.007	+.001
	—0.002	—.002	—.007
	—0.001	—.001	—.013
		(Jan. 27; 3 discordant	+.001
		observations due to	+.007
		passing clouds or	+.001
		smoke are omitted.)	—.012
			+.001
average logarithmic deviation	.002	.004	.006
average deviations	0.5 percent	0.9 percent	1.4 percent

These extrapolated determinations may now be compared with the values of the solar radiation computed by the spectrobolographic method. The results are summarized in Table II.

TABLE II

Date.	Log. a.	a.	Range of Air Masses.	Solar Radiation via Actinometer.	Grade.	Solar Radiation via Bolograms.	Grade.	Percentage Correction Necessary to Actinometer Values.
Oct. 9, 1902	0.113	0.771	1. 5–3.0	1.91	Very good	2.19	Fair	15%
Feb. 19, 1903	0.114	0.769	1. 8–2.9	1.97	Very good	2.27	Very good	15
Mar. 25, 1903	0.148	0.711	1. 4–2.6	1.96	Excellent	2.23	Excellent	14
Mar. 26, 1903	0.133	0.736	1. 3–2.3	1.82	Excellent	2.09	Excellent	15
Apr. 17, 1903	0.126	0.748	1. 2–1.9	1.90	Very good	2.18	Passable	15
Apr. 29, 1903	0.170	0.676	1. 1–1.6	1.75	Bad	1.96	Very good	12
July 7, 1903	0.177	0.665	1.06–1.5	2.07	Short, good	2.14	Poor	3
Oct. 14, 1903	0.107	0.780	1. 6–3.0	1.87	Very good	1.96	Very good	5
Dec. 7, 1903	0.085	0.822	2. 2–3.7	1.69	Excellent	1.94	Passable	15
Dec. 23, 1903	0.077	0.838	2. 2–3.1	1.75	Doubtful	1.99	Passable	14
Jan. 27, 1904	0.090	0.813	1. 9–4.0	1.77	Excellent	2.02	Fair	14
Feb. 11, 1904	0.113	0.771	1. 7–2.9	1.99	Very good	2.26	Fair	14
May 28, 1904	0.121	0.757	1. 1–1.9	1.97	Very good	2.09	Poor	6
Oct. 5, 1904	0.145	0.716	1. 5–2.7	2.02[1]	Very good	2.32[1]	Excellent	15
Nov. 16, 1904	0.095	0.803	2. 0–3.8	1.71	Very good	1.98	Passable	16

[1] Some doubt exists whether these values are not both too high, owing to a possible change in the constant of the actinometer due to an accident.

The first column contains the date of the observation; the second the tangent of the slope of the curve, and is equal to the logarithm of the value of "*a*" in Bouguer's formula; the third, this "*a*"; the fourth, the range of air-masses of the actinometer values; the fifth, extrapolated value of the solar radiation via the actinometer; the sixth, an estimation of the quality of the actinometric series; the seventh the solar radiation via the bolographic process; the eighth an estimation of its quality, and finally in the ninth the percentage correction necessary to bring the actinometer extrapolation in accordance with the bolometric value.

The table shows, as Mr. Langley demonstrated, that the values from the actinometer are too low. It is surprising, however, that the correction to be applied seems so nearly the same, averaging about 14 per cent., nearly independently of the transparency of the air or from what air-masses the actinometer extrapolation is made.

There are but three notable exceptions to this in the table: of these the one of October 14, 1904, is undoubtedly caused by a defect in the latest actinometer value. The other two are extrapolated from very small air-masses where, as will be shown, smaller corrections are to be expected, but besides this the bolographic observations were poor on these latter dates, and in the case of July 7, 1903, too small a range of air-mass was available to suitably determine the extrapolation.

Referring again to the remarkable and unexpected uniformity of the differences between the actinometric and bolometric extrapolations, it seems desirable to see how far this uniformity accords with what theory would lead us to expect. The analytical discussion, however, becomes very complex except in some comparatively simple hypothetical cases, so that the following graphical method has been employed. By the same process used in the bolometric extrapolations, actinometric values may be computed for any desired air-masses. In the accompanying figure 63 are shown two curves thus derived. Curve (A) was computed for March 25, 1903, a day of comparatively great general absorption, and curve (B) for October 14, 1903, a day of small general absorption, but both days of moderate water-vapor absorption. The abscissae are of course air-masses, the ordinates are the logarithms of the computed actinometer readings. It would have been better to have used more extreme cases, *e. g.*, a day of great general and great water-vapor absorptions, together with one when the absorptions of both these kinds were small. Such days, however, were not available. The values of "*a*" for these days as varying with the wavelength are given in Table III.

TABLE III

Percentage Transmission for Vertical Rays.

Date.	μ 0.40	μ 0.45	μ 0.50	μ 0.60	μ 0.70	μ 0.80	μ 0.90	μ 1.0	μ 1.2	μ 1.6	μ 2.0
Mar. 25, 1903,	47	50	57	66	72	76	79	81	84	88	89
Oct. 14, 1903,	64	70	76	80	85	88	89	91	91	(92)	(92)

These curves given in figure 63 show what the actinometer should have read according to the bolographic observations. With air-mass

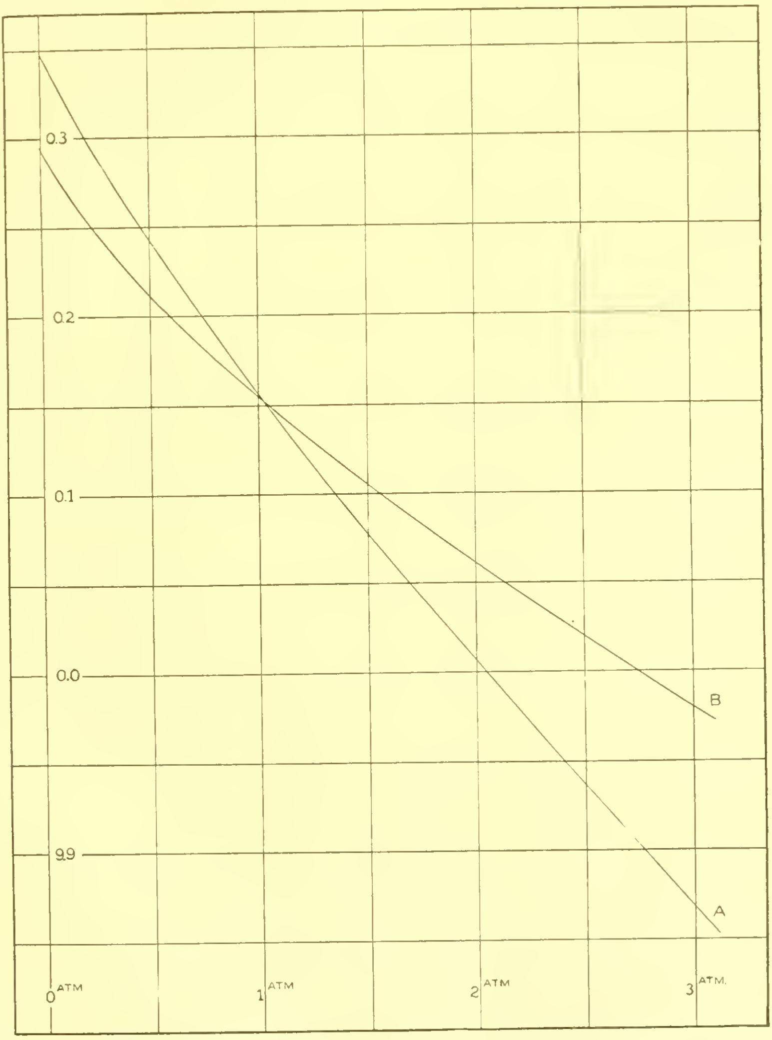

FIG. 63.—Curves of Solar Radiation computed from Spectro-bolometric Measures. Abscissæ are air-masses. Ordinates are logarithms of radiation.

1.0 the value is what would have been obtained with the sun in the zenith, but the points for air-masses between 1.0 and zero are purely hypothetical and do not exist in nature. That is, the point at air-mass 0.5 is not what the actinometer would have read had it been carried above the earth vertically until half the atmosphere lay below it, for such a value we have not the means of computing. It is the radiation that would be observed after passing vertically through a column containing one-half the actual absorbing medium, but with the same distribution of densities as actually exist in the zenith section of our atmosphere. In other words instead of removing the *bottom* layers in order to diminish the air-mass below unity a portion of *each* layer is imagined removed.

An inspection of this plot shows at once several points which Mr. Langley pointed out.[1]

"(1) that the coefficient of transmission" (which is the anti-logarithm of the tangent to the curve) "is not constant; (2) always too large under any circumstances; (3) always larger and larger as we approach the horizon, and (4) *that the original energy of the sun or star before absorption, as found by the thermometric processes and formulae in universal use, is always too small."* Also that the rate at which the tangents change becomes less and less the greater the air-mass.

Extrapolations, similar to those performed with the actual actinometry, have been made from the computed curves of figure 63. In the following table are given the corrections thus determined, together with "log a" and "a," as found from the slope of line used for extrapolation.

Range of Air Masses Used for Extra-polation.	1.0–1.5			1.5–2.0		
	Log *a*	*a*	Correction.	Log *a*	*a*	Correction
Mar. 25.	.157	.697	9 %	.142	.721	13 %
Oct. 14.	.098	.798	10	.092	.809	13
	2.0–2.5			2.5–3.0		
Mar. 25.	.139	.726	15 %	.137	.730	16 %
Oct. 14.	.085	.822	17	.082	.828	19

It thus appears that in extrapolation from ordinary air-masses varying from 1.5 to 2.5, a correction of 14 to 15 percent *would* be expected.

It is apparent from the table that the *air-masses* from which the extrapolation is made is an important consideration; the smaller the

[1] *American Journal of Science* (3), XXVIII, p. 163, 1884.

air-mass the smaller the correction. However the greater the air-mass, the straighter becomes the actinometer curve and therefore the less the variation in the correction as a function of the air-mass. On the other hand it is to be noted that the correction is not much affected by quite a considerable change in the transmissibility of our atmosphere. It might seem, *a priori,* that the amount of water-vapor present in the air would be an important factor; a small amount of aqueous vapor corresponding with a smaller correction; nevertheless the value of the correction derived from February 19, 1903, a day of phenomenally small water-vapor absorption, does not bear this out. Further study seems, however, necessary on this point.

It would be depending too far on the accuracy of the curves shown to use them as a basis for the determination of secondary corrections like those for changes in water-vapor absorption or general transmission coefficients. It seems apparent from the earlier table of comparisons, however, that in extrapolating from such air-masses (1.5–2.5) as are generally involved, a correction of 14 percent should be added to the resulting actinometer value. This corrected value then would probably be of nearly the same order of accuracy as if bolometrically determined.

For other places of the same altitude as Washington, and where the air-masses used would be nearly the same, it seems very probable that the same correction might apply, provided the transmissibility of the air was within the limits examined here.

For places of greater altitude the correction, although in all probability much smaller, might possibly be more variable.

In order to extend the scope of actinometric observations the actinometer in use here may be compared with several of the Ångstrom type in use at the Weather Bureau, and from this the comparison may be extended to other stations in this country and elsewhere supplied with Angstrom pyrheliometers. Thus the value of the radiation in units comparable with those used here, may probably be determined for other and perhaps earlier days than those here included. As the correction may be assumed constant for all stations in or near Washington, any actinometer observations made in this locality may serve to determine the correction at other places where simultaneous observations have been made.

It should be borne in mind that the determinations here are not regarded as absolute but are only relatively comparable among themselves. The great variation in actinometer readings at different places and by different instruments is probably often due to the difficulty of reducing their readings to an absolute scale of units. So that although the readings with two different instruments may seem discordant, yet all the readings with each instrument may be relatively quite comparable. While it is much to be desired that a uniform and if possible an absolute system of actinometry should be generally adopted, yet from the conclusions reached in this paper, it appears that even now any good series of actinometric observations on record may be possibly reduced to yield values proportional to the bolometrically determined ones, and all these may later be brought to a common system.

Mr. Abbot hopes soon to have his continuously recording standard actinometer in operation, and it was for use with this instrument that this research was undertaken, and I wish to express my obligation to him here for his continuous help and suggestions in preparing this paper.

Conclusion

By the application of a definite empirically determined correcting factor, the use of Bouguer's formula with actinometer measurements alone may serve to determine the extra-atmospheric value of the solar radiation with nearly the same accuracy as by the bolometric method. This correction for Washington is about 14 percent, additive, when the observations are between the air-masses 1.5 and 2.5.

It seems probable that the same correction would be applicable at other stations having, 1st, nearly the same altitude; 2d, similar air-masses, and 3d, similar atmospheric transparency,—this latter condition being determinable by the slope of the actinometer curve.

It is hoped that the correction may be later more accurately determined both as a function of the air-mass as also of the coefficient of atmospheric absorption, and that it may even be extended to places of much higher altitude.

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