THE ABSORPTION OF WATER VAPOR IN THE INFRA-RED SOLAR SPECTRUM

BY F. E. FOWLE, JR.

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

PURPOSE OF THE PAPER

The quantitative investigation of the relationship between the amount of water vapor in the terrestrial atmosphere and the corresponding changes in the transmissibility of the latter to the incoming solar energy, is the primary object of this paper. Bouguer's formula, which will later be treated in detail, furnishes an analytical means for this study. As generally used, however, it would indicate that the absorption depends only on the amount of vapor present as an absorbent; that is, the same absorption would be produced by a given quantity of water in the form of vapor, whether the path were long through a small density, or short through a great density. In order to determine spectroscopically the amount of aqueous vapor present in our atmosphere, it is necessary that such a condition should be true; in such a case, only, is it immaterial what distribution of densities exists in the atmospheric strata.

Janssen[1] finds, however, that certain oxygen bands do not satisfy this condition; neither does carbonic acid gas, according to Ångström.[2] Consequently it is important to find whether or not the absorption due to water vapor is expressed by Bouguer's formula in its ordinary form.

---

[1] J. Janssen, *Report British Association for Advancement of Science,* Bath, p. 547, 1880.

[2] Knut Ångström, *Annalen der Physik,* Band 6, p. 163, 1901. Somewhat analogous variations are observed with some salt solutions. See E. Müller, *Annalen der Physik,* Band 12, p. 767, 1903.

INTRODUCTION

The region of the solar spectrum observed at the Smithsonian Astrophysical Observatory, under the direction of Mr. Langley, is particularly adapted to this study of the spectroscopic absorption of atmospheric water vapor between wavelengths 0.68μ and 2.0μ. At the time of the publication of the first volume of the *Annals* of this Observatory, although some attempts had been made at quantitative measures in the atmospheric bands and other places in this region of the solar spectrum, the results were very meager.[1] The bolograms then taken, made for the determination of the deviations and wavelengths of the various absorption lines and bands, were not adapted to measures of the ordinates or intensities. The plates were taken at insufficient speed, and no determinations of the zero of ordinates were made except at the beginning and the end of an hour's run. A subsequent trial proved but little more fertile.

Within the last two years, in the bolographic study of the general atmospheric absorption[2] and the solar constant of radiation, bolograms have been taken at twenty times the speed formerly employed, and the zero of ordinates is now determined nearly every minute during the run. Moreover, owing to the improved bolometric apparatus, the drift has been reduced to such an extent that no more now may occur in a week than formerly often occurred in an hour. Consequently these recent bolograms are far better suited to the present discussion of the ordinates, although unfortunately the effective dispersion used is much too small for the best results.

This paper, then, is devoted to the application of Bouguer's formula to measures of the transmission of our atmosphere in the various absorption bands between B $(0.687\,\mu)$ and ω_2 $(2.05\,\mu)$. These various bands are indicated in plate I, which consists, in figure I, of two superposed bolograms, one of February 19, 1903, of very small water vapor absorption, the other of September 14, 1903, and of great water-vapor absorption. The bands may be tabulated as follows:

TABLE I

B,	atmospheric	oxygen,	wavelength	0.687μ
a,	"	water vapor,	"	0.718
A,	"	oxygen,	"	0.760

---

[1] Chapter VII, p. 205, vol. I, *Annals of the Astrophysical Observatory of the Smithsonian Institution,* 1900.

[2] *Smithsonian Reports* for 1902 and 1903. S. P. Langley, *Astrophysical Journal,* XVII, p. 89, 1903, and XIX, p. 305, 1904. C. G. Abbot, *Smithsonian Miscellaneous Collections* (*Quarterly Issue*), vol. 45, p. 74, 1903.
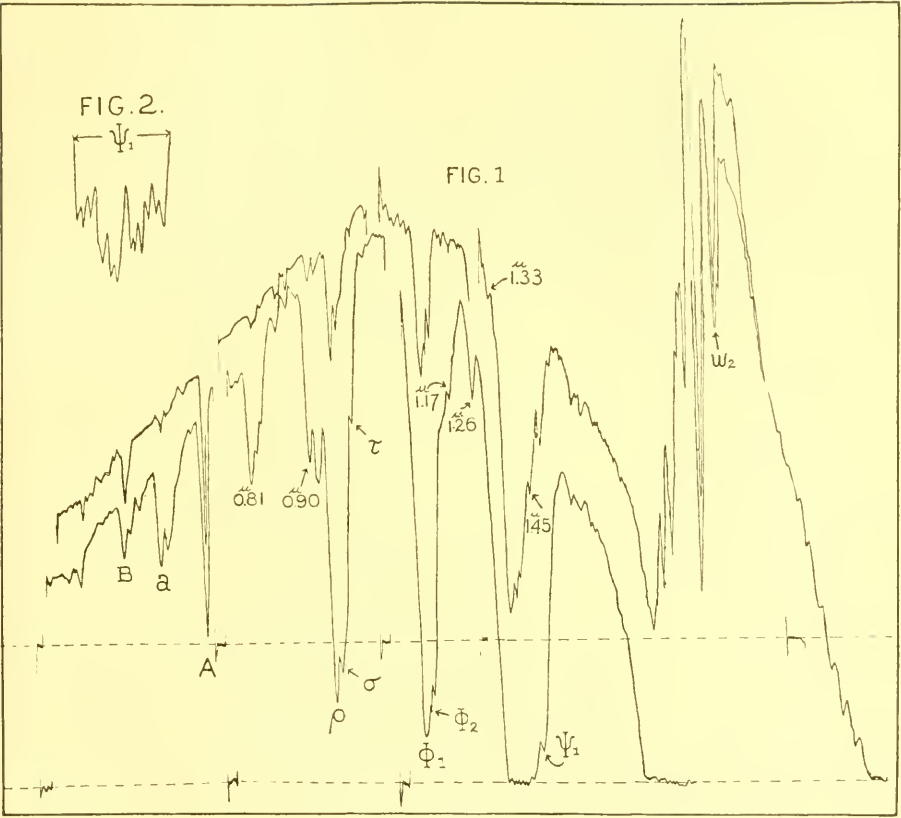
BOLOGRAPHIC ENERGY CURVES OF THE SOLAR SPECTRUM OF A 60° GLASS PRISM

Fig. 1, Spectrum between wavelengths 0.66 μ and 2.0 μ: (Upper curve, February 19, 1903, small water-vapor absorption; Lower curve, September 14, 1903, great water-vapor absorption). Fig. 2, Detailed structure of band Ψ_1.

	atmospheric water vapor, wavelength	0.814
—,	" " " "	0.896
μ,	" " " "	0.933
σ,	" " " "	0.945
τ,	" " " "	0.974
ψ_1	" " " "	1.119
ψ_2	" " " "	1.134
—,	" " " "	1.172
—,	" unknown absorbent, "	1.265
—,	" water vapor, "	1.331
—,	" " " "	1.451
η_1	" " " "	1.469
w_2	" unknown absorbent, "	2.049

That the A line and the deepest portion of B are due to atmospheric oxygen, has been shown by Egoroff.[1] A comparison of the two curves in figure 1 of plate 1 shows the presence, however, of considerable water vapor absorption in the "tail" of B. a was found by Ångström[2] to be due to water vapor. With the exception of the lines at 1.265 μ, 1.331 μ, and 2.049 μ, probably the earliest evidence of the origin of the others is in the work of Abney and Festing.[3] For the bands including $\rho\sigma\tau$ and those of shorter wavelengths, the evidence rests most directly in their variations in intensity between moist and dry days. Paschen[4] finds Υ and Ω in the emission spectrum of water vapor. Most of the bands, including Υ, are shown in curves for the absorption of liquid water made by Abney and Festing.[5] Moreover, the evidence for the water vapor bands (including that at 1.33μ), given in plate 1, figure 1, and plates IV and V, should be conclusive of their origin. This does not necessarily mean that the particular "nicks" in the curves are atmospheric; they may be due to some solar line superposed on the greater atmospheric band. By far the greater portion of the absorption must, however, be terrestrial.

BOUGUER'S FOMULA

Before proceeding with the bolographic observations in these bands, the formula by which it is hoped to express these measures of

---

[1] N. Egoroff, *Comptes rendus de l'Academie des sciences,* 97, p. 555, 1883; 101, p. 1143, 1885. See also A. Cornu, *Annales de chimie et de physique* (6) 7, pp. 5–105, 1886.

[2] A. Schellen, *Die Spectralanalyse,* vol. 2, p. 32.

[3] Capt. Abney and Col. Festing, *Proceedings Royal Society of London,* 35, p. 80, 1883.

[4] F. Paschen, *Annalen der Physik und Chemie,* 52, p. 226, 1894.

[5] Abney and Festing, op. cit., p. 333.

atmospheric transmission should first be considered. Bouguer's formula in a somewhat modified form may be written—

$$c = kd = c_0 a^{m\delta \frac{\beta}{\beta_0}} \tag{1}$$

where c is the amount of energy of a particular wavelength as received after its passage through the atmosphere. It is equal to the deflection, d, of the galvanometer, multiplied by a constant, k, a function of the receiving apparatus.

c_0 is the amount of this energy which would have been received had there been no terrestrial absorbing medium in the path of the rays.

a, the coefficient of atmospheric transmission, is equivalent to the fractional amount of energy transmitted by a unit layer. The unit layer of water vapor is taken to be such that, if condensed into a stratum of liquid water of the same cross-section, it would be one centimeter thick.

m, the air mass, is the length of the path of the ray through the earth's atmosphere. The unit "an atmosphere" is the length of the path with the sun in the zenith.[1]

$\dfrac{\beta}{\beta_0}$ is the ratio of the observed barometer β to the standard height $\beta_0 = 760$ mm. As the variations in β have not amounted to more than one percent, this factor has been neglected.[2]

[1] $m = \dfrac{\text{Refraction}}{58''.36 \times \text{sin. zenith distance}}$; James D. Forbes, *Philosophical Transactions of the Royal Society of London*, 1842, part 1, p. 225.

[2] This barometric term is, however, very misleading. The terrestrial atmosphere produces at least three kinds of absorption, due respectively to dust, to the permanent gases, and to the fluctuating vapors. It seems improbable that absorption due to the dust above a station varies with the barometer as indicated by the formula, for taking in illustration an extreme case of a cyclonic low barometer, the correction would imply less absorption, whereas the ascending currents may carry the dust into the upper and purer stata of the air, while the incoming currents at the bottom bring in additional dust, so that the absorption is actually increased. In ascending from one station to another at a higher altitude, the factor again affords no correct indication of the decrease of the absorption due to dust, unless indeed the decrease of barometric pressure follows the same law as the decrease in dust contents. In the second case of the absorption of the permanent gases of the atmosphere, the use of the barometric pressure seems legitimate for observations at a single station; for stations at different altitudes the partial pressure due to the gas causing the absorption should be used. Water vapor is an example of the third kind of absorbent, and a special factor for its transmission is introduced in the formula.

δ equals the amount of water vapor in the atmosphere. It is tentatively determined according to a formula given by Hann,[1] where $\delta = \varepsilon_0 \,(.23)$; ε_0 is the vapor pressure, in centimeters, at the surface of the earth, as deduced from readings of the wet and dry thermometers. Unfortunately water vapor measures were not taken during the times of taking these holograms, originally made for a purpose not requiring such measures, and it has been necessary to use in place of contemporary data, observations taken at 8 P. M., and kindly furnished by Mr. Willis L. Moore, Chief of the United States Weather Bureau.[2]

Bouguer's formula in its logarithmic form,

$$\log d = \log \frac{c_0}{k} + m\delta \log a, \qquad (2)$$

with $\log d$ and m as variables, is used in plates II and III, shortly to be described; but in plates IV and V the formula has been further modified, as follows: The fractional transmission due to the water vapor alone, apart from the dust of the air, has been used in place of kd, so that, assuming all the absorbing vapor to be terrestrial, c_0 becomes unity and we have, calling D this fractional transmission,

---

[1] Dr. Julius Hann, *Lehrbuch der Meteorologie*, Leipzig, 1901, p. 225.

[2] These, with other data incident to the holograms, are tabulated below (Table II); the second column gives the range of air masses between which observations were used. In the last column the condition of sky is given; 1 being as good as possible, 3 would be useless for observation:

TABLE II

Date.	Air-Masses.	Thermometer.		Baro-meter.	Water vapor in one atmosphere.	Remarks.
		Wet.	Dry.			
1902				in.	cm.	
Sept. 11	1.2 to 2.2	60.1 F	69 F	30.0	2.46	Sky 1, calm, then light S. W. winds, cirri.
Oct. 2	1.6 to 2 6	57.9	62	30.0	2.54	Sky 1, calm.
15	1.6 to 4.2	47.0	53	29.9	1.50	Sky 1.
16	1.4 to 3.1	53.8	56	29.9	2.28	Sky 1–2, calm.
22	1.6 to 3.6	45.5	50	30.1	1.49	Sky 1, calm, cold.
Nov. 15	1.9 to 5.7	60.0	68	30.0	2.51	Sky 1–2, warm.
1903						
Feb. 19	1.6 to 3.1	14.0	15	30.5	0.39	Sky 1–2, cold, cloudless all day.
Mar. 3	1.5 to 2.4	39.8	46	30.4	1.03	Sky 1.
25	1.4 to 3.4	39.0	44	30.0	1.06	Many cumuli, N. W. wind.
26	1.2 to 3.4	46.0	53	30.1	1.36	Sky whitish but fine, N. W. wind.
Apr. 17	1.5 to 2.3	49.5	56	29.7	1.65	Sky whitish, many cumuli.
28	1.1 to 2.5	56.0	70	30.1	1.71	Sky 1, calm; light S. W. wind at end
29	1.1 to 2.3	62.0	77	30.0	2.27	Sky 1, milky blue.
Dec. 23	2.2 to 3.4	33.5	39	30.3	0.76	Sky clearest since long time.

$$D = a^{m\delta} \tag{3}$$

or

$$\log D = m\delta \log a \tag{4}$$

$\log D$ and δ being then used as the variables. The values of a in equations (2) and (4) are not identical but are related as indicated in equations (5) and (6) below.

FIRST METHOD OF DETERMINING THE TRANSMISSION COEFFICIENT

The treatment of the observations for finding the transmission coefficient of water vapor may thus follow two independent procedures. In the first method the sun is observed at various altitudes on the same day, thus altering the amount of the absorbent by changing the length of the path of the beam through it, while the density, δ, of the absorbent remains constant. The effect of diminishing proportionately the path of the ray in every one of the horizontal layers of the earth's atmosphere containing the absorbing medium is thus followed, and from the knowledge so gained it may be possible to pass by extrapolation to the case where each layer is zero and there is no absorption. In the case of high and low sun measures at a single station, the exact vertical distribution of the absorbent is immaterial to the legitimacy of Bouguer's formula, provided the distribution is constant during the observations, and uniform, at equal altitudes, over moderate horizontal air layers. The unit layer of water vapor would have the same distribution of density that exists in the actual vertical atmospheric column.

It may be objected that the water vapor in the air is too fluctuating for any such treatment, yet it seems from the spectroscopic evidence, which follows, that there are days when conditions are fairly constant, seldom during the morning hours, but more often during afternoon. Oftentimes a month may pass without such days in this locality.

In plates II and III are shown some of the data plotted according to this method. The abscissæ are " atmospheres " and the ordinates the logarithms of the galvanometer deflections. These plots, according to Bouguer's formula, should be linear, and generally are so. A still further test, however, may be applied. For each date and wavelength two series of points are plotted. The lower points correspond to the ordinates at the bottom of the deflections, the upper to the smooth curves drawn across the tops of the bands, representing what the ordinates would have been had there been no absorption from the gas or vapor under consideration. If the absorption were
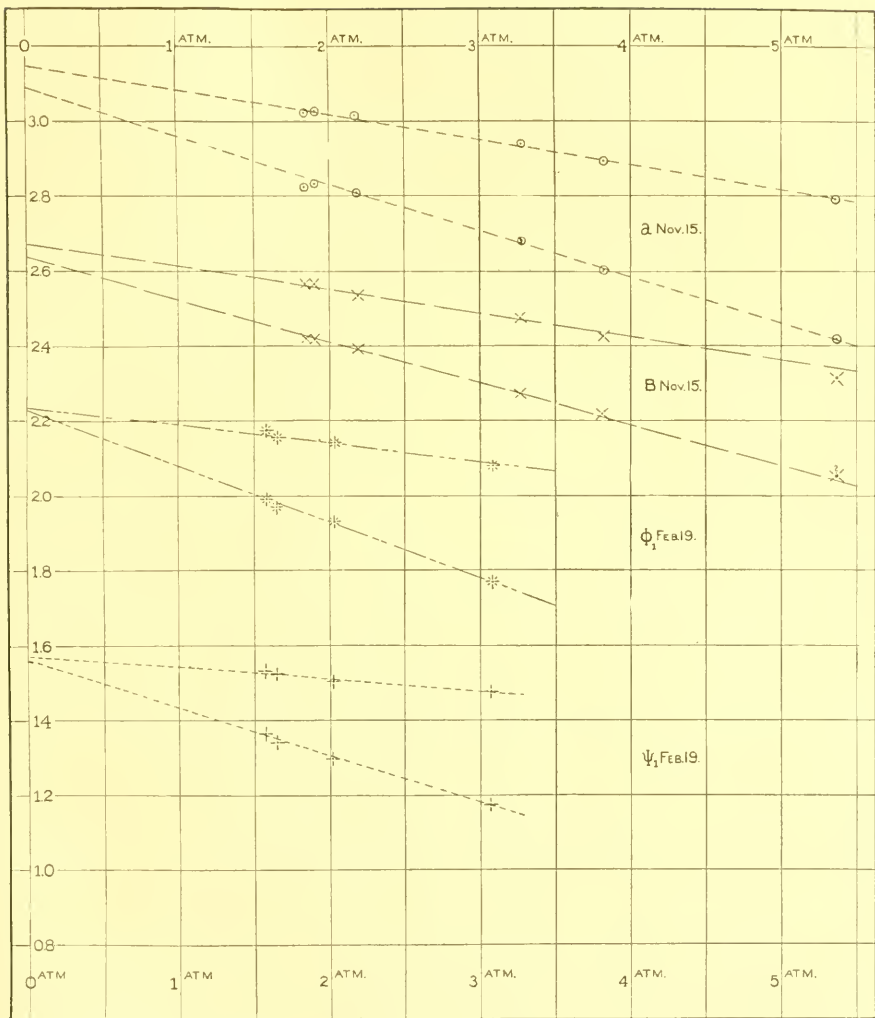
DETERMINATION OF TRANSMISSION COEFFICIENTS OF ATMOSPHERIC WATER VAPOR BY CHANGING
LENGTH OF PATH IN THE ABSORBING MEDIUM
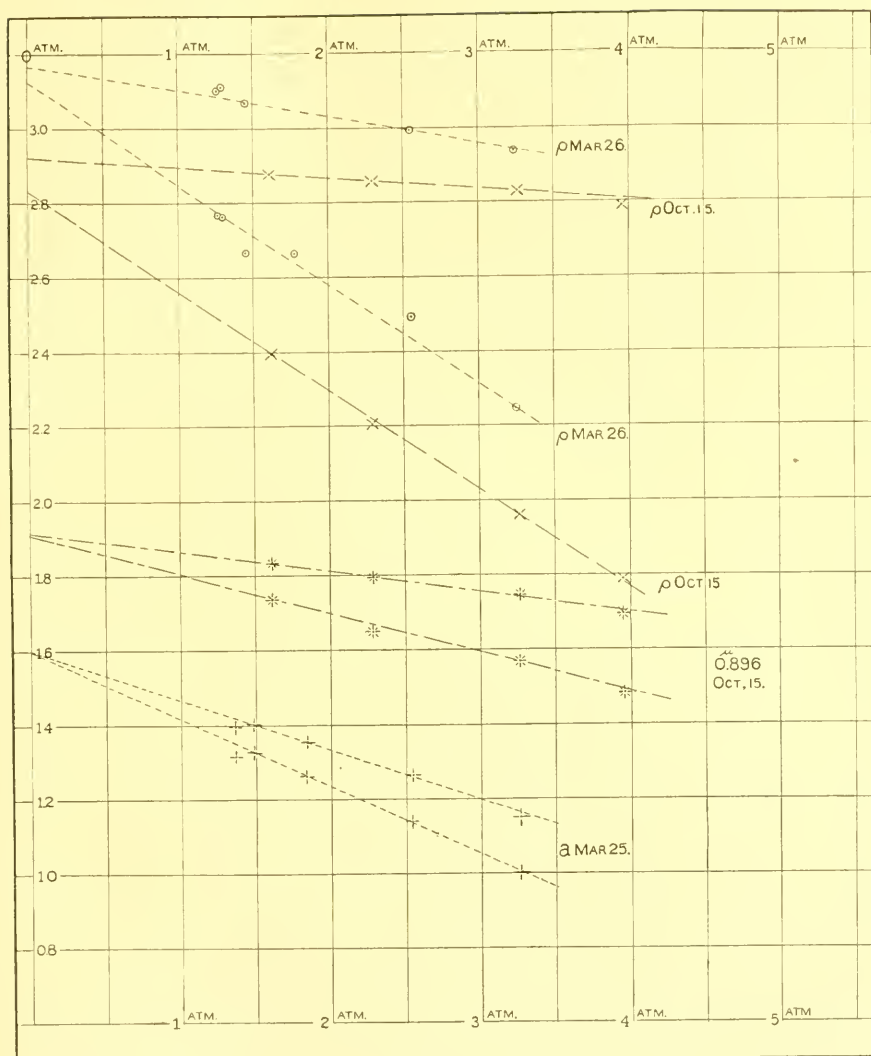
DETERMINATION OF TRANSMISSION COEFFICIENTS OF ATMOSPHERIC WATER VAPOR BY CHANGING
LENGTH OF PATH IN THE ABSORBING MEDIUM

solely terrestrial, the two lines thus determined should intersect on the line of zero atmospheres.[1]

This condition is probably as well fulfilled as can be expected, considering the impurity of the spectrum. Probably the upper line of each pair suffers little in its accuracy from this impurity; but as to the lower line—the small dispersion, the slit width, the bolometer width, the time of swing of the galvanometer needle, the speed with which the spectrum is passed over the bolometer,[2] and the composite character of the lines all tend to make the deflections too great. Figure 2, plate I, shows the composite character of Ψ_1 as shown in detail bolograms of 1898; and this may be compared with the same band in figure I under the present conditions. Moreover the greater the absorption in the band, the more it is influenced by these conditions, and all tend to make the bolographic ordinate at the bottom too great, and to cause the lower line of each pair in the plots to reach the line of zero atmospheres below the upper line. For days and lines of very great absorption, the deflection becomes so small in some of the greater bands that the error from the uncertainty of the zero is an important additional factor.

However, despite these limitations, as shown in plates II and III, extrapolations to without the earth's atmosphere have filled up the bands as follows:

TABLE III

Date	Band.	Ratio of Ordinate of Band to that of Smoothed Curve.[3]	
		At Earth's Surface. Air Mass = 2 Atmospheres.	Outside Atmosphere Air Mass = 0 Atmospheres
November 15, 1902.	a	0.65	0.90
" " "	B	0.71	0.93
February 19, 1903.	Φ_1	0.61	0.99
" " "	Ψ_1	0.62	0.98
October 15, 1902.	ρ	0.27	0.81
" " "	0.896μ	0.77	0.99
March 25, 1903.	a	0.80	1.00
" 26, "	ρ	0.35	0.90

[1] The absorption, however, may not be solely terrestrial on account of the possible superposition of some solar line as previously indicated. The depth of some solar lines is quite great. The ratio of the energy at the bottom of the C line to that indicated by a smooth curve across its top, is certainly less than 0.70. For the H and K lines it is certainly less than 0.15.

[2] The difference of deviation from A to ω_2 was 130′; the slit width subtended from 10″ to 15″, the bolometer width 16″; the spectrum passed over the bolometer at a speed of 20′ in one minute of time; and the time of a single swing of the galvanometer needle was about $1\frac{1}{2}$ seconds. No correction has been made for these.

[3] See also similar data in columns five and six of Table IV.

It should not be inferred from this table that the values of the solar radiation outside the atmosphere, determined here, are too low. In solar constant determinations the smoothed curve alone is used, and, as just indicated, the deficiency in plates II and III is probably nearly wholly due to the errors of observations in the bands.

The determinations of the transmission coefficients by this method are tabulated in the next section.

SECOND METHOD OF DETERMINING THE TRANSMISSION COEFFICIENT

The second method of applying and testing the formula is to observe the sun at the same altitude or air mass on days of different densities, δ, of water vapor. Since it has been impracticable to observe the sun always at such a standard altitude or air mass, which in the present discussion has been taken as one and one-quarter atmospheres, the observations have required a small correction by means of Bouguer's formula, in order to reduce them to this standard air mass. The corrections, in general, have been small. The observations, reduced according to this second method, are plotted in plates IV and V, where the abscissae are the equivalent layers of water vapor present in the path of the beam, and the ordinates the logarithms of the fractional transmission. As these observations have been taken with a comparatively high sun, they are not so much subject to the sources of error mentioned in the previous section, although without doubt they are still affected by them.

The observations seem to conform remarkably well with the formula, if we except the group including April 17, 28, 29, and September 11. It may be seen from Table II, that on April 17 there were many cumuli; on April 28 a change in the wind during the latter part of the observation; and on September 11 there were many cirri. The constants of the apparatus might have been different on those days, rendering the purity of the spectrum less, but although the appearance of the plot for the very deep and narrow A line may seem to support this view, that of ω_2 does not. Possibly during the months of increasing water vapor in the atmosphere there is some lag of the upper air in conforming with Hann's equation for the amount of water vapor present. In drawing the straight line representing the data, this discordant group has been neglected.
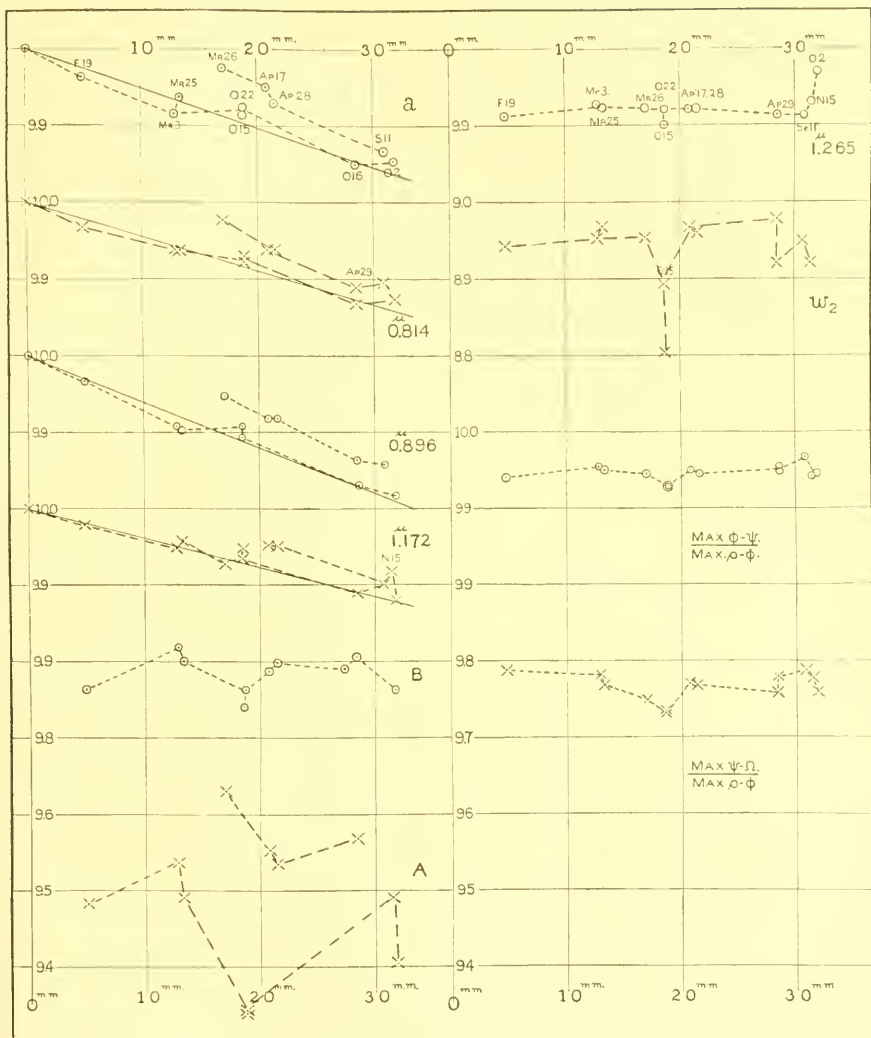
TRANSMISSION COEFFICIENTS

The value of the transmission coefficient a, of one centimeter of liquid water in vapor form, may be determined in two ways: First, referring to plates II and III, if a_1 is the transmission coefficient ob-
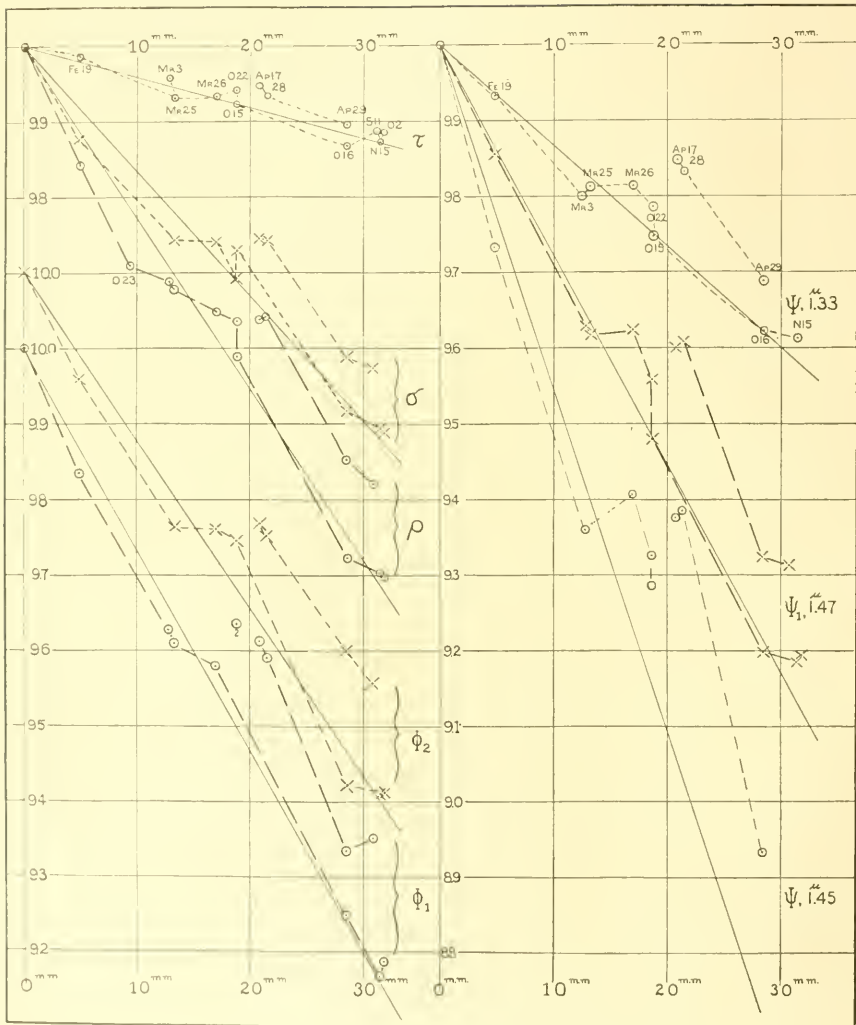
DETERMINATION OF TRANSMISSION COEFFICIENTS OF ATMOSPHERIC WATER VAPOR BY CHANGING
DENSITY OF ABSORBENT

DETERMINATION OF TRANSMISSION COEFFICIENTS OF ATMOSPHERIC WATER VAPOR BY CHANGING DENSITY OF ABSORBENT

tained from the upper line of a pair, a_2 that corresponding to the lower, and a the coefficient for the water vapor alone, then

$$\log a = \left(\log \frac{a_1}{a_2}\right) \div \hat{o} \qquad (5)$$

And in the second place, referring to plates IV and V.

$$\log a = \frac{\log A}{m\hat{o}} \qquad (6)$$

The values of these transmission coefficients for the various water vapor bands are exhibited in the following table:

TABLE IV

| Band. | Wave-length. | Transmission Coefficient. | | Continuation of Columns 3 and 4 of Table III. | | Date for Last Three Columns. |
		Second Method Density of Vapor Varying.	First Method Length of Absorbing Stratum Varying.			
a	0.718μ	0.889	0.94	0.65	0.90	Nov. 15, 1902
			0.90	0.80	1.00	Mar. 25, 1903
—	0.814	0.902	0.91	0.66	0.99	Oct. 16, 1902
			0.92	0.83	0.99	Mar. 25, 1903
			0.92	0.69	0.95	Apr. 29, 1903
			0.93	0.80	0.99	Apr. 17, 1903
—	0.896	0.871	0.87	0.90	1.00	Feb. 19, 1903
			0.92	0.65	0.99	Apr. 17, 1903
			0.92	0.62	0.95	Apr. 29, 1903
ρ	0.933	0.594	0.62	0.37	0.98	Mar. 3, 1903
			0.61	0.10	0.91	Oct. 16, 1902
			0.65	0.13	0.91	Apr. 29, 1903
			0.71	0.32	0.93	Apr. 17, 1903
σ	0.945	0.683	0.69	0.18	1.00	Oct. 16, 1902
τ	0.974	0.909	0.91	0.64	0.97	Oct. 16, 1602
Φ_1	1.119	0.541	0.54	0.61	0.99	Feb. 19, 1903
			0.53	0.06	1.02	Oct. 16, 1902
			0.56	0.30	1.00	Mar. 3, 1903
Φ_2	1.134	0.599				
—	1 172	0.916				
Ψ	1.331	0.736				
Ψ	1.451	0.355				
Ψ_1	1.469	0.529	0.55	0.62	0.98	Feb. 19, 1903
			0.55	0.06	0.95	Oct. 16, 1903
			0.59	0.08	0.80	Apr. 29, 1903

The fifth and sixth columns are continuations of the last two columns of Table III. Column five indicates the amount of radiation transmitted in the band at an air mass of two atmospheres, expressed as a fraction of the amount which would be found if there were no water vapor absorption. Extrapolating to zero both from the band and from the smoothed curve over the band, as in plates II and III, it may be found how nearly the band is obliterated outside the atmos-

phere by employing Bouguer's formula. The absorption still remaining is indicated by the difference between the transmission so found as given in the sixth column, and unity. As would be expected from the sources of error indicated in discussing the first method of obtaining the transmission coefficients, the value of the coefficient obtained by varying the air mass, m, is generally greater than that obtained by varying the density, δ, of the water vapor.

Several reductions with the air mass, m, varying are included in the table for April 17 and 29 of the discordant group of days previously mentioned. It will be observed that the difference between the values in the third and fourth columns is here greater than usual. Now, assuming that the values of the transmission coefficients of these different bands obtained from the observations of all the days but those of the discordant group by varying the density are correct, these values (a) and the corresponding values of a_1 and a_2 may be substituted in equation 5, page 9, to determine new values of δ for the days in question. These, reduced to an air-mass of 1.25 atmospheres for comparison with plates IV and V, are:

$$\text{April 17, 1903,} \quad 1.31, \quad 1.24, \quad 1.36, \quad \text{mean } 1.30$$
$$\text{April 29, 1903,} \quad 2.41, \quad 2.41, \quad 1.94, \quad \text{mean } 2.25$$

If these values had been used for the corresponding points in plates IV and V, the data for these dates would not then have been discordant.

In plate V are plotted the values for the transmission for the bands B and A, due to oxygen, and for the bands at $1.285\,\mu$ and ω_2, of unknown atmospheric origin. There are also plotted the ratios of the ordinates at the maxima between Φ and Ψ, and between Ψ and Ω, to those between ρ and Φ. All of these plots are apparently independent of water vapor. It is improbable that any conclusion can be drawn as to the origin of the bands at $1.285\,\mu$ and ω_2 from comparison with the plots for the oxygen bands. The irregularities in A are probably due to its great depth and narrowness, so that the ordinate at its bottom depends very greatly on the instrumental conditions.

RELATION OF ABSORPTION TO DENSITY OF ABSORBENT

Very little is yet known of the change of absorption of a vapor in passing to the liquid form, except from measures of the total absorption over the whole spectrum. Those oxygen bands which have an absorption varying with the square of the density, still seem

to follow the same law when the absorbent is in liquid form.[1] Saturated steam, according to Very,[2] exercises more total absorption over the whole spectrum than the same amount of water vapor under atmospheric conditions. Water in liquid form goes still further in this direction. " A layer of water 40 centimeters thick is almost absolutely impervious to solar infra-red radiation beyond the wavelength 1.0μ. No such absorption occurs with the moist humid air as the sun approaches the horizon, although the absolute amount of water in a vaporous form interposed in the path of the rays must be even greater than that contained in a layer 40 cm. thick."

However, Paschen says : " In the liquid state there is a continuous general absorption, whereas in the gaseous form only a discontinuous absorption and emission spectrum is found, there being no indication of a continuous superposed absorption or emission." It may be very possible that the selective absorption in these water vapor bands follows the same law of density when the absorbent is in liquid form, and that the general absorption causes the great increase in opacity observed. The last two curves in plate V certainly show no differential effect between the maxima from μ to Φ, Φ to Ψ, and Φ to Ω, due to a general water vapor absorption. It is hoped to discuss this point further in a subsequent paper.

Probably the only available measures on the absorption of liquid water, comparable with those on water vapor, contained in this paper, are those made by Abney and Festing.[4] Their results give, with layers of ½ inch and 1¾ inches liquid water respectively, in μ, 78 and 19 percent transmitted, and for Φ, 69 and 2 percent. The logarithms of these numbers are 9.89, 9.28, 9.84, and 8.30, respectively. The first three lie above, the last below the lines indicating the absorption of aqueous vapor in plate II. However, little weight can probably be attached to the comparison, on account of the probable difference in the effective purity of the spectroscopes used.

SUMMARY

The selective absorption of water vapor within the range of densities observed seems to depend only on the amount of the

[1] J. Janssen, *Report British Association for Advancement of Science,* Bath, p. 547, 1880. G. D. Liveing and Dewar, *Philosophical Magazine* (5) 40, p. 268, 1895.

[2] F. W. Very, *Bulletin G, U. S. Weather Bureau,* p. 94, Washington, 1900. Ångström finds the general absorption of CO_2 increases more rapidly than with the first power of the density. Knut Ångström, *Annalen der Physik,* Band 6, p. 163, 1901.

[3] *Annalen der Physik und Chemie* 52, p. 221, 1904.

[4] *Proceedings Royal Society of London,* 35, p. 328, 1883.

absorbent present, and is well expressed by Bouguer's formula. In other words, the absorption produced by a given quantity of water in the form of vapor is the same whether the path is great through a small density or vice-versa. Considering successive bands, for example 0.81μ, $\rho\sigma\tau$, Φ, Ψ, Ω, it may be noted that the selective absorption of water vapor is not greatest, like the general absorption, at the shorter wavelengths, but increases as the wavelengths of the bands increase. It varies from 10 percent in the more shallow bands near A, at 0.76μ, to nearly 100 percent in the bottom of Ω at 1.80μ, where only on exceedingly dry days is much indication of energy detected.

However, in the separate bands themselves, where the increase in absorption on reaching the bands from the shorter wavelength side is quite sudden, the absorption then more slowly decreases, like the general absorption, with increasing wavelength.

The best values for the transmission coefficients are those in the third column of Table IV. They give the fractional amount of the incident energy transmitted by a layer of water 1 cm. thick in the form of vapor.

No indication of a general water vapor absorption in the region from 0.68μ to 2.00μ has been found.