COLLECTED ARTICLES AND DATA RELEVANT to the DEVELOPMENT AND OPERATION of the NRAO INFRA-RED HYGROMETER commonly known as the LOW METER

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(10 copies)

Foreword:

The Low portable water meter has been an important instrument in regard to site surveys for radio and infra-red astronomy. I believe that the value of the instrument lies (1) in simplicity and ruggedness of its design and (2) in the choice of a water-vapor band having a dynamic range appropriate for evaluating astronomical sites. Its accuracy is also well-matched to the intrinsic sampling errors unavoidable in most site surveys of atmospheric water vapor.

Unfortunately, most of its development is chronicled in unpublished papers and internal reports which can be easily lost from astronomical history.

This report is a collection of the fundamental articles, reprinted from the rare and often dog-eared copies in my files. I hope that this anthology will preserve the history of the Low meter for a little longer.

-- M. A. Gordon

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Paper 1: "A Spectral Hygrometer for Measuring Total Precipitable Water", by N. B. Foster, D. T. Volz, and L. W. Foskett.

This is a fundamental reference for the measurement concept. It includes the empirical relationship between radiosonde observations of water vapor and the IR ratio used to calibrate the Low meters.

Paper 2: "A Comparison of Mean Precipitable Water-Vapor at Several Selected Locations Using An Improved Type Water-Vapor Hygrometer", by F. J. Low.

This include the first results of the <u>portable</u> Low meter, the original distribution list for the meters, and the calibration curve for model A(3-1). Gerard Kuiper carried A(3-1) to many sites world wide. It was used for the LBL reports on water vapor written by Kuiper. Its zero-point calibration was made by Francis Gary Powers from a U2 aircraft over Tucson, Arizona. This meter, now broken, was in the possession of Arnold Davidsen in Tucson as of January 1986.

Paper 3: "Measurements of Atmospheric Attenuation at 1 Millimeter and a Description of a Portable Spectral Hygrometer", by F. J. Low and A. W. Davidsen.

This paper gives a detailed technical description of the fixed and portable Low meters and reports some observational results of the fixed meter.

Paper 4: "Calibration of an Atmospheric Water Vapor Meter by Means of Synthetic Spectra", by T. N. Gautier and U. Fink. This important but unpublished work confirms that the square-root of pressure correction is appropriate for measurements taken with the 0.935 micron band. (It is not correct for other water bands, however).

Data: The spectral transmission of the filters for Low meter "C", resident at the NRAO 12-m telescope on Kitt Peak. The filters of this instrument have changed little since it was built.

This paper, printed in its present form as a manuscript in limited quantity, was presented at the 1963 International Symposium on Humidity and Moisture, Washington, D. C., May 20-23, 1963. As this reproduction does not constitute a formal scientific publication, any reference to the paper in published articles and scientific literature should identify it as a manuscript of the U. S. Weather Bureau.

UNITED STATES DEPARTMENT OF COMMERCE

WEATHER BUREAU

A SPECTRAL HYGROMETER
FOR MEASURING TOTAL PRECIPITABLE WATER

by

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and

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June 1963

A Spectral Hygrometer
for Measuring Total Precipitable Water

by

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U. S. Weather Bureau, Washington, D. C.

ABSTRACT

This paper describes a recording photoelectric spectral hygrometer developed by the U. S. Weather Bureau for determining the amount of water vapor in a vertical column of the atmosphere. Basically, the hygrometer monitors the relative radiant intensity of direct solar energy transmitted in a water-vapor absorption band. A sensing path directed at the sun is maintained by means of a motor-driven equatorial mounting.

The intensity of the radiation in the selected region of absorption is compared to that of a nearby

region having essentially no absorption. The region of absorption is centered at 0.935 micron and the reference region at 0.881 micron. Narrow-band-pass interference filters isolate the two spectral regions. Silicon solar cells are used as radiation detectors.

The instrument is designed so that the ratio of the photocurrents is proportional to the ratio of the transmitted radiant energies. Continuous ratio measurements are automatically obtained on a recording, self-balancing ratio bridge. Calibration depends on an empirical method involving simultaneous values of total precipitable water calculated from radiosonde observations.

Both laboratory tests and trial operation have demonstrated the dependability of the spectral hygrometer. Its stable design makes it suitable for use in the operational activities of meteorology as well as in research.

1. Introduction

Those interested in forecasting precipitation have for many years felt the need for a field instrument that would provide a continuous record from which the total precipitable water[1] could at any time be readily determined. It is possible to make an approximate computation of the total precipitable water from radiosonde observations, but this is a time-consuming procedure.

The absorption spectra method employed in the near infrared region of the solar spectrum is, we believe, the most practical means of measuring total precipitable water. The fundamental technique was first described by Fowle (1912). The method with respect to this hygrometer consists of isolating two narrow regions of the solar spectrum: one in a suitable water-vapor absorption band, the other in a nearby region where no absorption occurs. A ratio is established between the irradiance in these two regions. A change of water-vapor concentration in the sensing path changes the ratio. However, when the radiant flux changes due to haze, smoke, mist, etc., the ratio remains essentially unaltered.

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[1] The term, total precipitable water, is used in accordance with the definition given in the Glossary of Meteorology (1959).

Thus the ratio can be used as an index of the amount of water vapor in the sensing path. The latter quantity can then be divided by the appropriate optical air mass value in order to determine the vertical atmospheric water-vapor content (total precipitable water).

2. Physical concepts

The water-vapor absorption bands are identified with the vibrational and rotational motions of the water-vapor molecules. Ascribed to the three normal modes of vibration of these molecules are three intense bands centered in the infrared near 6.27 µ, 2.77 µ, and 2.66 µ. The last two of these overlap considerably, thereby forming a broad region of absorption that is often referred to in the singular as the 2.7-µ band. A number of other bands, representing various multiples and combinations of the fundamental frequencies, occupy spectral positions from 3.17 µ to 0.57 µ. The more prominent bands of this group are centered in the near infrared at approximately 1.88 µ, 1.38 µ, 1.14 µ, and 0.93 µ (see Fig. 1). A detailed identification of the vibrational components of the water-vapor spectrum can be found in a paper written by Adel and Lampland (1938). Molecular rotation also contributes to the formation of the bands described above. In a sense, rotational motions serve to shape these bands around the central wavelengths provided by the vibrational motions. Also contained in the water-vapor spectrum is the strong and extensive band that lies in the far infrared beyond the so-called 10-µ window; this band is attributed solely to the effects of rotation. To conclude this brief description of the water-vapor spectrum it seems appropriate to note that the bands diminish in strength more-or-less gradually toward the shorter wavelengths, with those in the visible region exhibiting relatively little absorption.

Care should be exercised in the selection of a band for use in measuring water vapor. A band should be chosen with an intermediate range of fractional absorption for the amount of water vapor likely to be contained in the sensing path. If the absorption is too strong, total absorption may occur when the water-vapor content is high. If the absorption is too weak, the instrument will suffer in sensitivity and instrumental errors will tend to mask true values. The central region of the 0.93-µ band gives a satisfactory range of fractional absorption for the amount of water vapor usually encountered in the path of normal incidence to the sun through the earth's atmosphere (Foster and Foskett, 1945). A nearby region in the vicinity of 0.88 μ exhibits little or no absorption and therefore serves as an excellent region of reference.

In a spectral region of continuous absorption the relationship between the absorption and the absorbing mass can be expressed as a simple exponential function. However, such a function does not accurately describe the absorption that occurs in the water-vapor bands, since these are not of a continuous character. Actually these bands consist of numerous closely-spaced lines; moreover, the line patterns are irregular in spacing and intensity. The absorption that occurs in a band having such irregularities is actually a complicated process not precisely describable by a simple mathematical formula. Nevertheless, a relationship between the absorption and the absorbing mass does exist, and the curve approximating this relationship in a particular band, or subinterval thereof, can be established by empirical means. Furthermore, in most cases a relatively simple square-root expression closely describes this curve through a limited range of the fractional absorption.

Elsasser (1937, 1938, 1942, 1960) formalized the square-root absorption law, which relates specifically to subintervals within the infrared water-vapor bands. The square-root law states that the fractional absorption A which occurs in an atmospheric layer of finite thickness is directly proportional to the square root of the absorbing mass X and the square root of the atmospheric pressure P, and inversely proportional to the fourth root of the absolute temperature T. If isobaric and isothermal conditions prevail throughout the layer, then the equation

$$A = K(XP)^{1/2}T^{-1/4} \qquad (1)$$

can be used as an expression of the square-root law. In this equation the factor K is a dimensional constant that depends on the units in which the variables are expressed as well as the spectral characteristics of the particular subinterval under consideration. Elsasser demonstrated that the square-root law closely describes the actual absorption curve in the range of relatively small to intermediate values of the fractional absorption. The reader is directed to the references cited above for further information concerning the limitations of the square-root law as well as for details pertaining to its formulation.

The equation presented above clearly indicates that the absorption spectra method, as it is implemented in this scheme of measuring total precipitable water, is marked by a degree of uncertainty due to the dependence of the absorption process on the pressures and temperatures through which the atmospheric water vapor is distributed. The approximate mean effects of the distributional relationships are obviously incorporated into the empirical calibration of the spectral hygrometer when radisonde observations provide the comparative data for calibration. We are therefore basically concerned only with the relative errors arising from distributional variations. These errors are briefly discussed in the following paragraphs.

A simple consideration based on Eq (1) shows that the absorption process is relatively insensitive to temperature in the range of temperatures through which the bulk of the atmospheric water vapor is distributed. This temperature range is small in an absolute sense, and the distributional profiles within this range are not excessively variant. Since the absorption varies only as the reciprocal of the fourth root of the absolute temperature, it becomes apparent that the relative errors introduced by the temperature effect are virtually insignificant.

A somewhat similar consideration, based on the same equation, shows that the pressure effect is not prohibitive. The bulk of the atmospheric water vapor normally appears in the lower troposphere. In other words, the vertical distributions of water vapor are weighted toward the higher pressures. Obviously, the absorption process is relatively less affected by incremental pressure variations at these pressures than at the lower atmospheric pressures. Soundings show that the vertical profiles of atmospheric water-vapor distribution are not excessively variant. In most cases, therefore, the pressure effect does not introduce serious relative errors in this method of measuring total precipitable water.

Howard, Burch, and Williams (1955) observed that the fractional absorption in the entire 0.93-μ band actually varies more nearly as the fourth root, rather than the square root, of the atmospheric pressure. The weaker pressure dependence in the observed case is attributed to overlapping of neighboring spectral lines. The spacing and intensity of the spectral lines—and hence, also the degree of overlapping—are variable in the water-vapor spectrum. Each wavelength interval has its own characteristic fine structure. With this in mind it seems reasonable to conclude that the pressure dependence of the absorption region of the spectral hygrometer, which monitors only a fraction of the wavelengths in the 0.93-μ band, should differ from that of the entire band. Theoretical considerations as well as some general experimental evidence given in the above-cited report lead us to believe that the actual pressure dependence of this particular absorption interval falls somewhere between the square-root and fourth-root relationships. Further research is obviously needed in this respect.

In their report, Howard, Burch, and Williams (1955) suggest that the actual effect of temperature might also be smaller than indicated in the formal relationship represented by Eq (1). They note that overlapping of neighboring spectral lines should be affected not only by pressure, but also by temperature, since both of these variables appear in the theoretical expression for the width of a spectral line. Thus the argument for ignoring the temperature effect gains even more support. At this point it seems appropriate to note that the slight uncertainties due to the temperature effect should merely serve to partially offset those due to the pressure effect. Considering that temperature as well as pressure decreases with altitude in normal atmospheric profiles, Eq (1) clearly shows that the absorption is opposingly affected by pressure and temperature when a vertical displacement of water vapor occurs.

In view of the foregoing discussions it appears that an empirical calibration of the spectral hygrometer should follow closely, through a limited range of fractional absorption, the simple equation

$$A = K'X^{1/2}. \tag{2}$$

In this equation the new constant K' incorporates factors representing the integrated mean effects of temperature and pressure as well as the factors ascribed to the constant K in Eq (1).

Thus far we have shown that the absorption spectra method can be expected to give fairly accurate relative measurements of total precipitable water. However, the dependence of absorption on pressure (and to a lesser degree, on temperature) implies that due consideration must be given to certain restrictions inherent to the application of this method:

a. The spectral hygrometer should be operated at elevations close to that of the location where it is calibrated.

b. Use of the instrument should be limited to a reasonable range of optical air mass values.

Obviously, the first restriction is relatively important. King and Parry (1963) describe an actual case, involving an experimental model of this instrument, which verifies this point. Independent calibrations for this instrument were obtained at two different elevations. A significant difference was observed between the two calibration curves, and an interesting relationship was found between the two curves. More research in this respect is highly desirable in order to determine whether an empirical relationship of this type is adaptable for general applications.

The second restriction is not operationally significant. Basically, it involves the question of whether the uncertainties due to the pressure effect are enhanced at any given fractional absorption when the latter is permitted to occur as a result of widely varying quantities of vertical water-vapor content. A preliminary study, involving vertical atmospheric profiles (water-vapor concentration versus pressure), shows that the variability in the slant-path profiles is not appreciably greater when these profiles result from a wide range of values of vertical water-vapor content compared to a relatively narrow range. Indirect evidence resulting from the empirical calibration procedure and experimental use of the spectral hygrometer also indicates that the uncertainties due to the pressure effect are not selectively magnified by optical air mass variability.

The discussion in the foregoing paragraph does not take into account the inherent uncertainties attending very low solar elevation angles. These uncertainties are primarily related to the effects of refraction and excessive scattering, and to possible timing errors associated with the rapidly-changing long optical paths.

3. Description of the instrument

The optical components. The two spectral regions of interest are isolated by first-order, narrow-band-pass interference filters. The filters are placed in the box housing in front of the photocells (see Fig. 2). In operation the solar beam remains at normal incidence to the filters since the hygrometer is continuously aimed at the sun. The following data summarize the normal-incidence characteristics of these filters: The filter that isolates the region of absorption has its central wavelength at 0.935 μ, a peak transmittance of 43%, and a half-width of 13 mμ; the filter used for isolating the reference region has its central wavelength at 0.881 μ, a peak transmittance of 50%, and a half-width of 13 mμ. =130 Å

Parallel tubes of 12-in. length and 1 7/8-in. i.d. are used for collimating the sunlight. Sharp-cutoff red filters, Corning C.S. No. 2-61 (transmittance <0.5% at wavelengths below 0.590 μ), are installed at the forward ends of the collimating tubes to provide protection from the weather as well as to prevent the transmission of radiation through possible passbands of higher order. In order to minimize errors due to internal reflections, a diaphragm with 1 3/8-in. i.d. is flush-mounted in the front end of each tube immediately behind the cutoff filter. A Plexiglas window is installed behind the collimating tube assembly, thereby isolating the box-housing chamber for more efficient thermostating of the photocells.

The photocells. Silicon solar cells with 1-in.-diam active surfaces are used as the radiation detectors. They are very fast in response ($\leq 20\ \mu$sec), and have exceptionally stable, long-life performance characteristics. A properly matched pair of these cells gives continuous ratios of the photocurrents in direct proportion to the ratios of the in-band to out-of-band solar energies. Laboratory tests verified the reliability of these cells.

Silicon solar cells exhibit a relatively high current response in the near infrared region at which this hygrometer operates. The spectral response range of this type of photocell extends approximately from 0.35 μ to 1.15 μ, with a maximum response occurring near 0.75 μ. The photocells used have a nominal efficiency of about 10% in the region of maximum response.

The response of these cells to incident light energy was found to be somewhat dependent on the ambient temperature. Temperature stability was achieved by thermostating the photocell mounting block at 100°F. This operating temperature also serves to prevent condensation from forming on the internal optical surfaces.

The current output of a silicon solar cell is directly proportional to the intensity of light incident upon its active surface when the load across the cell is small, approaching short circuit. Laboratory experiments were conducted to test the cells for linearity under increased external loads. The levels of illumination were adjusted so that the range of output current of each photocell was comparable to the range that it generates during normal operation of the spectral hygrometer. The results of these experiments indicate that under the simulated conditions of effective illumination the output current of this type of photocell begins to fall off very slightly from linearity as the external resistance is increased to values above about 10 ohms. This deviation was found to be relatively small even for resistances as high as 50 ohms. The deviation then increased more sharply for higher resistances. Although tests showed the nonlinearity to vary with different cells, it was found that by proper selection pairs could be matched for similar deviations. By installing a pair of matched photocells in the hygrometer and keeping the external resistances fixed at specific values less than 50 ohms, it was possible to obtain ratios of output current proportional to the ratios of incident radiant energy. The error in the obtained ratios was always less than 1/2% regardless of the overall intensity of the incident beam.

Fluctuations in the overall intensity of the incident solar beam are related primarily to the processes of scattering and diffuse reflection by the atmospheric constituents. The effect of the gaseous constituents is slight, and that of the nongaseous constituents such as smoke, dust, and haze is somewhat greater. But obviously the greatest effect is that of clouds. However, these light-attenuating mechanisms are essentially nonselective in the near infrared region within which the hygrometer operates. Therefore, since the hygrometer gives a linear ratio response with properly selected values for the fixed external resistances across the photocells, the ratio given by the hygrometer represents primarily a measure of the water vapor contained in the atmospheric sensing path regardless of the fluctuations in the overall intensity of the incident beam.

The foregoing statement is true only as long as the incident sunlight is sufficiently intense for the photocells to provide the minimum current necessary for the self-balancing ratio bridge[2] to find a balance point. In practice, when thin clouds appear in the path of the solar beam, a balance will occur only while the sun continues to cast relatively discernible shadows. In this case, the direct-beam intensity corresponds roughly to about 15% of that obtained with full sunlight. Below this level of illumination the response of the recorder fails rapidly, and the scale error increases quite sharply. Future experimentation may show that increased amplification will permit this hygrometer to give valid readings even though the sunlight is obstructed by denser clouds.

The equatorial mounting. In order to get a continuous record of water-vapor measurements, the hygrometer is placed

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[2] This circuit employes a conventional potentiometric recorder which has been modified for use as a ratio bridge.

on a motor-driven equatorial mounting (see Fig. 3) and trained on the sun. The mounting (also developed by the Weather Bureau) is weather-tight and capable of following the sun throughout the day without attention.

The ratio-bridge circuit. A schematic diagram of the self-balancing ratio-bridge circuit is shown in Fig. 4. The two photocurrents are fed into the bridge circuit. The ratio of the photocurrents is registered directly on the recorder chart. The following discussion with reference to Fig. 4 explains the relationship of the photocurrents to the recorded ratios.

Several considerations led to the arbitrary choice of 40.0 ohms for R_a and 20.0 ohms for R_s. Among the factors considered were ratio-bridge sensitivity, recorder resolution, standardization of the recorder readings to the hygrometer ratios, and linearity of hygrometer ratios (see discussion on photocells). Further laboratory tests of this hygrometer indicated that the linearity consideration requires a total of 36.0 ohms across the reference-band photocell when 40.0 ohms are placed across the absorption-band photocell. Consequently, the sum of R_b and R_t must be held constant at 16.0 ohms.

When a balance of the bridge occurs, the potential drop in one arm of the bridge equals that in the other. This is expressed by the equation $I_aR_a = I_rR_r$, from which we obtain the useful relationship $I_a/I_r = R_r/R_a$. The latter equation states that the ratio of the photocurrents varies inversely as the ratio of the resistances which are effective in the balancing process. This ratio of effective resistances is a direct function of the balance position of the bridge. Therefore the recorder gives a direct reading of the desired ratio of the photocurrents.

An example, in accordance with the designations in Fig. 4, clarifies the above relationship. As previously noted, R_a and R_s are fixed respectively at 40.0 ohms and 20.0 ohms. Assume in this case that R_b is set at zero and R_t at 16.0 ohms. (R_t is in the photocell loop, but never becomes part of the bridge circuit.) Now, if the recorder balances at half scale, R_e is 10.0 ohms and the ratio becomes $I_a/I_r = R_r/R_a = (R_b + R_e)/R_a = (0 + 10.0)/40.0 = .250$. Obviously these resistance values establish a ratio span of .000 to .500 across the recorder.

The hygrometer herein described normally operates in a range of ratios from .200 to .700, except with low solar elevations in very humid weather (see Fig. 5). The equation in the paragraph above reveals that the ratio span of the recorder is shifted to match the usual range of hygrometer ratios (.200 - .700) by simply setting R_b at 8 ohms. (R_t is then also set at 8 ohms.) In practice, R_b and R_t can be designed into the circuit so that corresponding increments (e.g., 4-ohm steps) can be simultaneously added and subtracted (or vice versa) by means of a 2-pole rotary selector switch. This step-resistance arrangement also facilitates the use of the recorder with any of several spectral hygrometers.[3]

4. Calibration

The calibration procedure consists of comparing the hygrometer ratios as shown by the recorder against the corresponding quantities of water vapor that exist in the respective sensing paths at the times of these comparisons. Usually the

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[3] The ratio range of a particular hygrometer depends primarily on the combined effects of the respective characteristics of the narrow-band-pass filters, the corresponding responses of the photocells, the relative solar intensities in the respective wavelength intervals, and the fractional absorption coefficient for the specific wavelength interval of the absorption passband.

amount of water vapor in the sensing path is expressed in inches (or centimeters) of precipitable water. Experience shows that no simple method of calibration is available. A calibration using laboratory facilities is not feasible because of the excessive path lengths required to duplicate the typical quantities of water vapor that exist in the atmospheric paths of the solar beam. Furthermore, laboratory techniques can only yield constant-pressure calibration data. Since theoretical and experimental knowledge regarding the pressure effect is still somewhat limited, adjustment of these data in an attempt to approximate average conditions prevailing in the solar-inclined atmospheric paths would, at this time, only add further complications and uncertainties. The decision was therefore made to obtain an approximate empirical calibration which makes use of radiosonde measurements.

The spectral hygrometer measures the amount of water vapor X in the atmospheric path of the solar beam, whereas the radiosonde measurement represents the approximate amount of water vapor W in a vertical column of the atmosphere. The calibration procedure therefore requires that the quantity determined from the radiosonde data must in each case be multiplied by a proportionality factor: the ratio of the length of the solar-inclined atmospheric path to that of the zenith atmospheric path. This ratio m, the optical air mass, is approximated by csc α, where α is the elevation angle of the sun. The optical air mass is expressed more precisely by Bemporad's formula[4], particularly for solar elevations below 20°. The solar elevation angle can be obtained from appropriate tables or curves, or it can be measured directly at the time of observation; the method used in determining this angle depends largely on the facilities available and the number and frequency of the desired observations.

The tentative calibration shown in Fig. 5 consists of a plot of the recorded hygrometer ratios R versus appropriate optical air mass multiples mW of the corresponding radiosonde evaluations of total precipitable water. All plotted points in this calibration were obtained from simultaneous observations taken at the Observational Test and Development Center[5], U. S. Weather Bureau, Washington, D. C., on favorable days from June, 1961 through April, 1962. A more precise calibration of this hygrometer is now being pursued.

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[4] Bemporad's formula together with computations in terms of z, the complement of α, can be found in Table 137 of Smithsonian Meteorological Tables, 6th rev. ed. (1951).

[5] Lat 38°59'N, long 77°28'W, elev 276 ft MSL.

5. Concluding remarks and discussions

Instrumental reliability. The following general statements are presented concerning the reliability of the spectral hygrometer:

a. Laboratory tests have proved the stability and linearity of the instrumental equipment. These tests showed that the accuracy of the hygrometer is not degraded by ambient temperature variations or by intensity fluctuation of the incident radiation.

b. Experimental operation has provided strong evidence of the dependability and relative accuracy of the instrument. Changes in total precipitable water as detected by the spectral hygrometer were quite consistently comparable to those changes indicated by successive radiosonde measurements, regardless of the altitude, and hence pressure, at which the changes occurred. Further confidence was established by means of another spectral hygrometer of the same design. The second instrument was operated simultaneously on an adjacent mounting during the calibration period. The records from the two instruments showed a striking agreement in relative measurements by consistently indicating identical changes in total precipitable water over both short and long periods of time.

c. A preliminary study of an approximate nature was recently made in an effort to obtain a numerical appraisal of the pressure effect. The associated computations involved variations in the vertical distributional profiles of water vapor as shown in roughly 150 radiosonde records obtained during the calibration period. Results of this study indicate that the pressure-induced uncertainties in this method of measuring total precipitable water should normally not exceed .03 to .05 inch. Extreme variations in the vertical profiles might cause occasional errors up to .10 inch. Further studies of this type together with more thorough knowledge regarding the pressure effect are required before a more definite statement can be made in this respect.

Possible applications. The availability of continuous measurements of total precipitable water suggests several distinct uses for the spectral hygrometer. Local correlation studies between total precipitable water and other meteorological variables become more feasible. These studies might include such factors as atmospheric stability, probability of precipitation or thunderstorms, amount of precipitation, or minimum temperature. An important application might be in the field of agricultural meteorology, especially with respect to the prediction of damaging frost. A suitable network of spectral hygrometers could provide important information regarding the movement and extent of moist tongues, which are of particular interest to the forecasters of severe weather. This type of network may also prove useful in conservation activities, particularly in the field of applied hydrology. Research in the realm of physical meteorology may offer further possibilities of instrumental application.

Acknowledgments. The authors wish to express their appreciation to Messrs. Elbert W. Atkins and Theodore Walters of the Observational Test and Development Center for providing technical assistance and facilities relevant to obtaining and analyzing the radiosonde data, to Dr. Earle K. Plyler of the National Bureau of Standards for his authoritative advice pertaining to water-vapor absorption bands, and to Mr. Ralph Stair of the National Bureau of Standards for providing spectrophotometric analyses of the narrow-band-pass filters.

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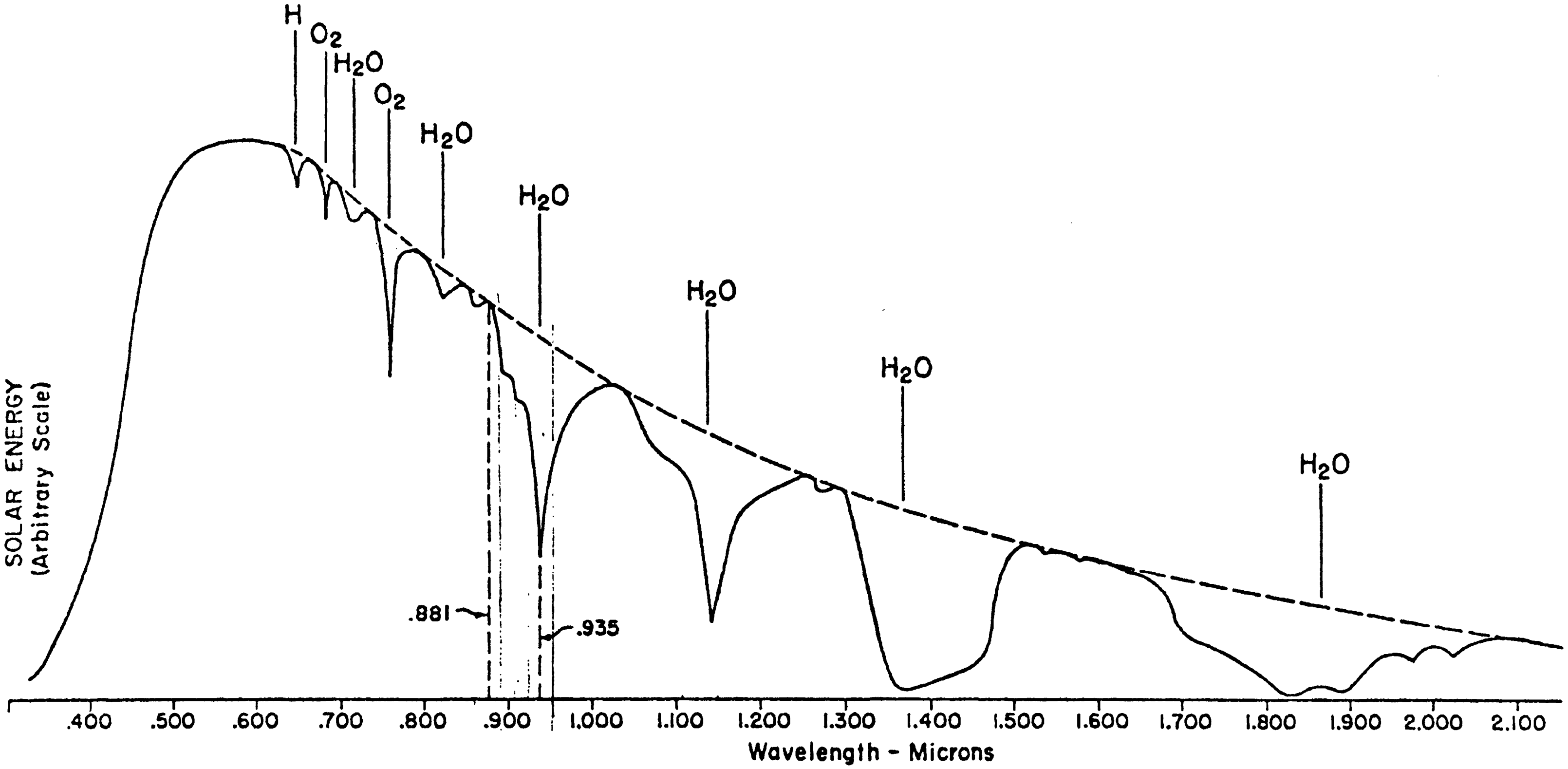


Fig. 1. Curve showing the approximate solar energy distribution at sea level through the visible and part of the near-infrared regions. Notation is made of the reference and absorption band centers. Some of the more prominent bands of absorption are indicated. Ordinates are in arbitrary units, not strictly to scale.

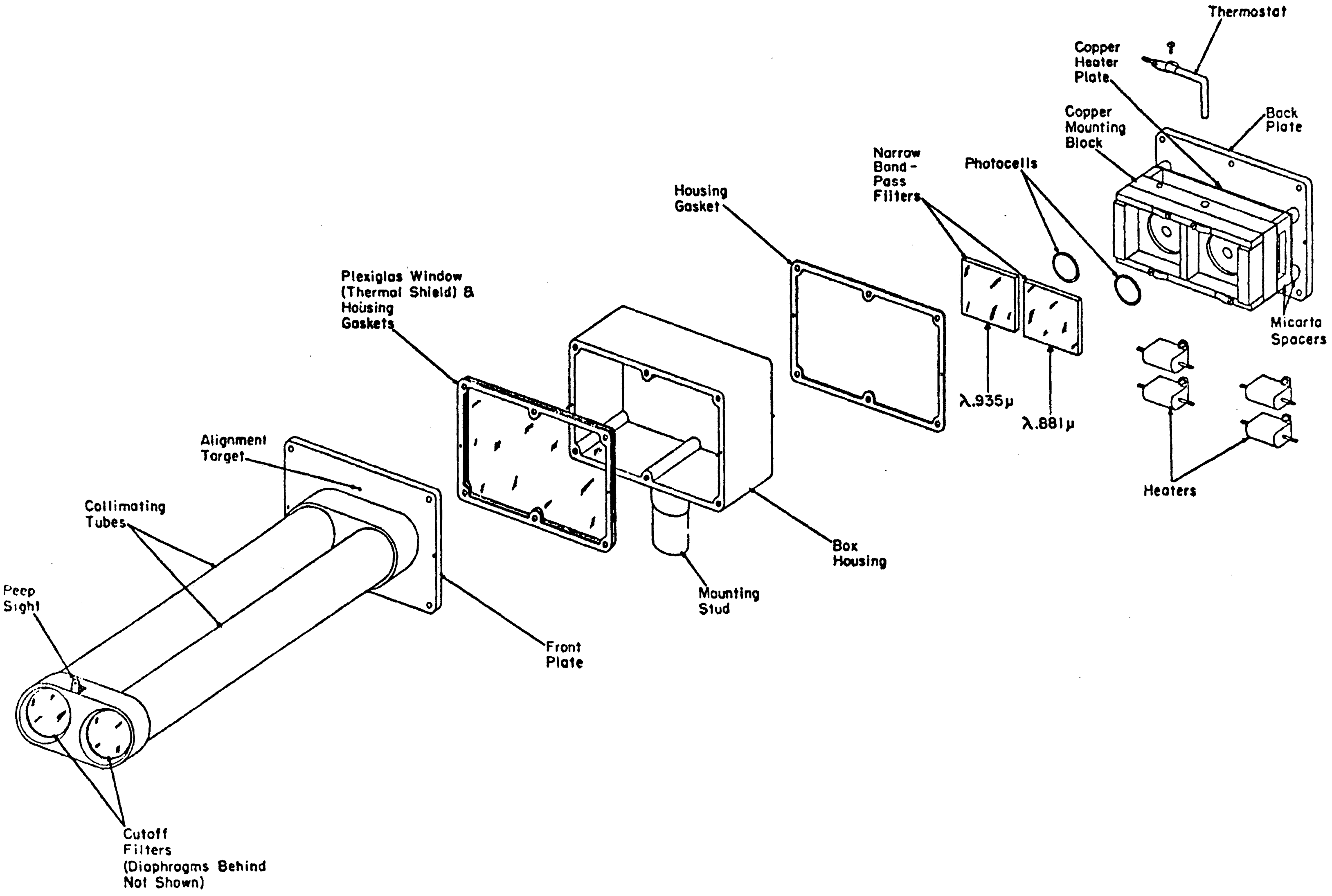


Fig. 2. Exploded view of the spectral hygrometer showing the relative orientation of the various components.

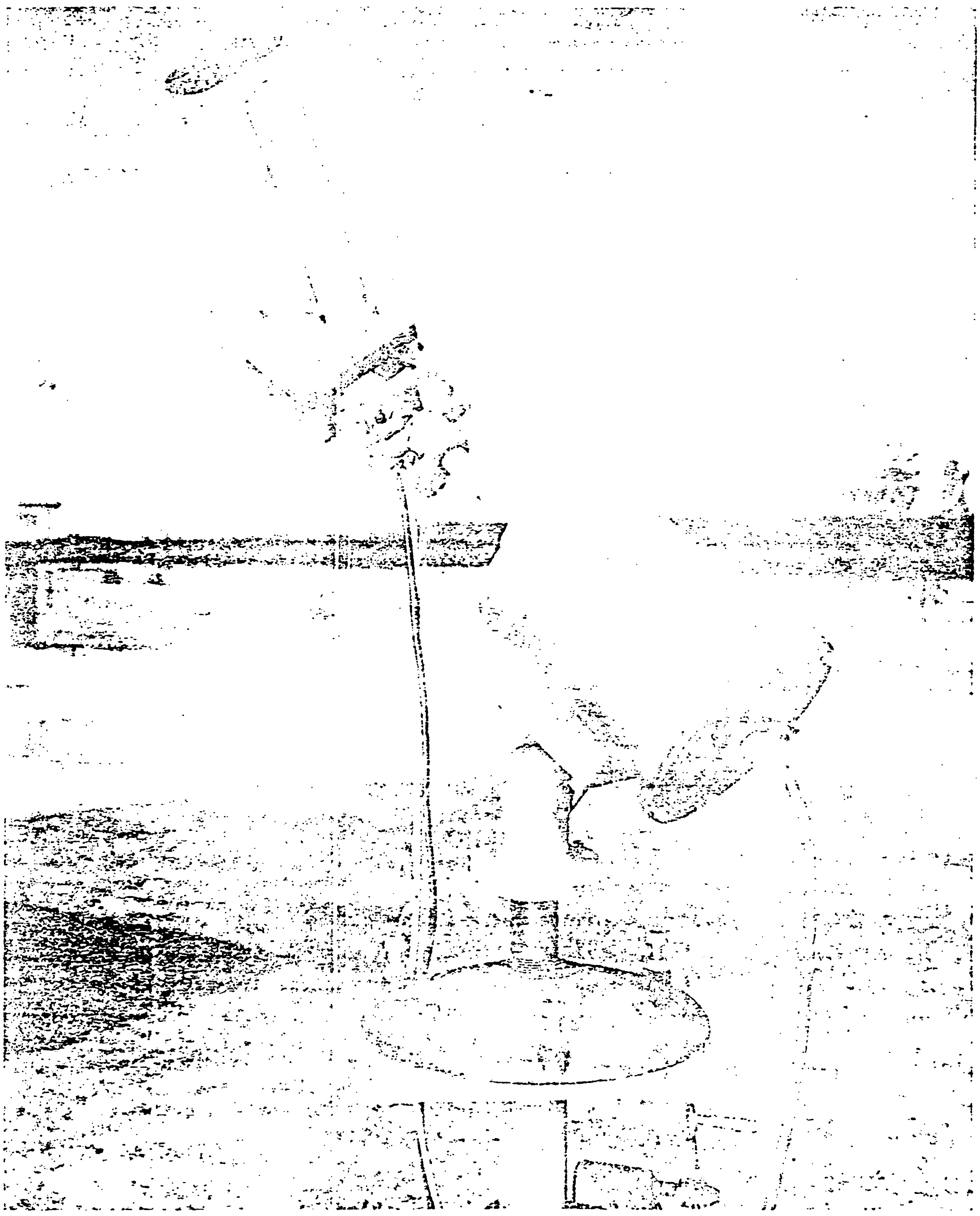


Fig. 3. Spectral hygrometer on an all-weather, solar-tracking equatorial mounting.

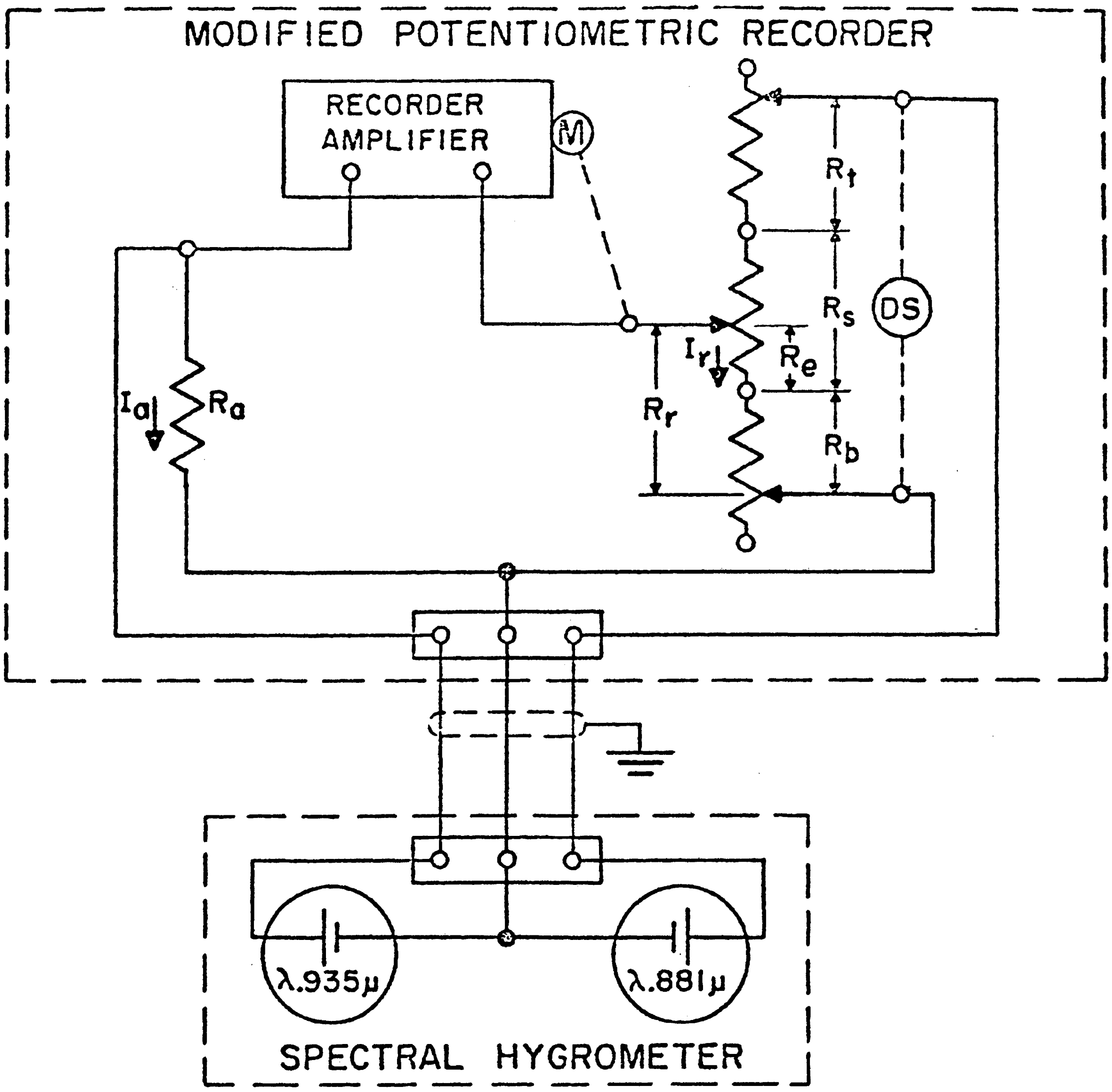


Fig. 4. Schematic diagram of the ratio-bridge circuit. I_a--current from the absorption-band photocell; I_r--current from the reference-band photocell; R_a--40.0 ohms, the total resistance across the absorption-band photocell, which is also across the input of the recorder; $R_r = R_b + R_e$--the part of the resistance in the reference loop that is effective in the ratio bridge (i.e., the total resistance below the balance point); R_s--20.0 ohms, the entire resistance of the slidewire; R_e--the part of the slidewire resistance below the balance point; R_b--zero suppression resistance, or the variable resistance below the slidewire which is used for shifting the ratio range of the recorder to match the operational ratio range of the hygrometer; R_t--compensating resistance, or the resistance above the slidewire which is varied simultaneously with R_b so that the external resistance across the photocell remains constant; DS--the 2-pole rotary selector switch which facilitates the simultaneous changing of R_b and R_t in equal amounts; M--the balancing motor.

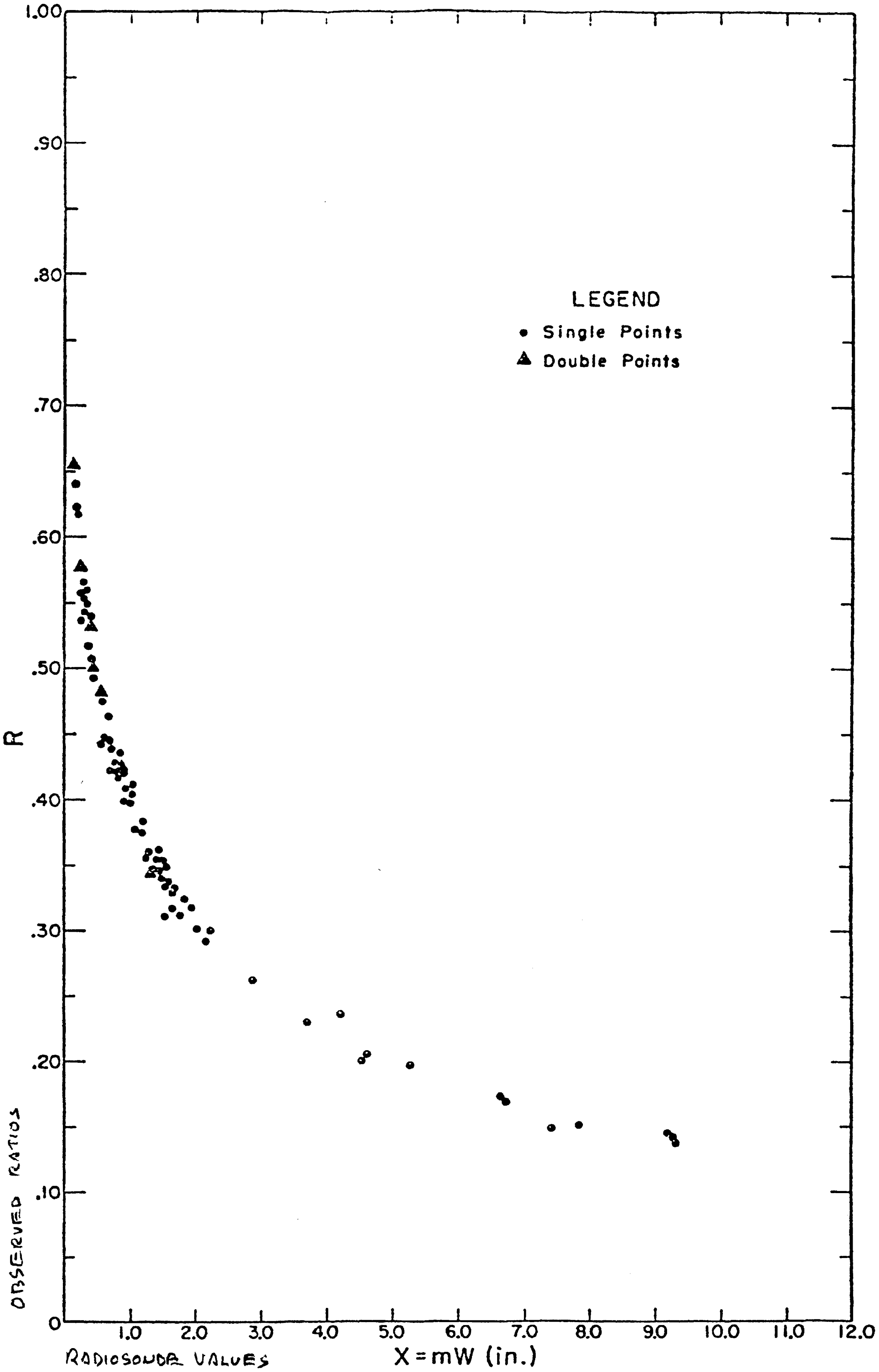


Fig. 5. The tentative calibration of the spectral hygrometer. The curve represented by the plotted points gives the mass of water vapor X in the sensing path as a function of the hygrometer ratio R. The total precipitable water can be readily determined by means of the equality W = X/m, where m represents the optical air mass at the time of observation.

NATIONAL RADIO ASTRONOMY OBSERVATORY
Green Bank, West Virginia

Millimeter Wave Internal Report

A COMPARISON OF MEAN PRECIPITABLE WATER-VAPOR AT SEVERAL SELECTED LOCATIONS USING AN IMPROVED TYPE WATER-VAPOR HYGROMETER

Frank J. Low

DECEMBER 1964

NUMBER OF COPIES: 30

THE NRAO PRECIPITABLE WATER SURVEY

During the past year the NRAO has developed and calibrated a number of portable spectral hygrometers for measuring total atmospheric water vapor. In addition to measurements made at Green Bank and at selected sites by NRAO personnel, we have been fortunate to receive data from the High Altitude Observatory, the University of Arizona, and Kitt Peak National Observatory. All of the instruments have been intercompared and the compiled data have been reduced to unit air mass. These data are given in tabular and graphical form.

It is anticipated that more data will be collected in the future and a recompilation will be made when necessary. The appendix describes the instrument, its use and calibration.

SITE DESCRIPTION

Green Bank, West Virginia

Located 180 miles west of Washington, D. C. at an elevation of 2690 ft.; site of National Radio Astronomy Observatory.

Kitt Peak, Arizona

Located 45 miles southwest of Tucson, Arizona, at an elevation of 6760 ft. Readings taken at the Solar Telescope of the Kitt Peak National Observatory.

Catalina Mountains, Arizona

Optical observing site of the University of Arizona, approximately 35 miles northeast of Tucson, Arizona at an elevation of 8300 ft.

Climax, Colorado

Seventy miles southwest of Denver at 11,150 ft.; the site of the High Altitude Observing Station.

Mt. Pinos, California

Located 60 miles northwest of Los Angeles; 8830 ft.

Jet Propulsion Lab, Pasadena, California

Elevation 770 ft.

Table Mountain, California

50 miles northeast of Los Angeles; 7500 ft. in height.

DISTRIBUTION OF HYGROMETERS

Hygrometer	Designation
*A(3-1)	Used by NRAO observers until July 1964 when it was taken to Kitt Peak.
A(1-3)	Sent to John Firor at Boulder, Colorado (3/16/64).
A(4-2)	At Climax, Colorado.
A(2-4)	Shipped 3/12/64 to Harold Johnson, Tucson, Arizona.
B(3-3)	Mailed to Bruce Gary, Jet Propulsion Lab, on 2/18/64.
B(4-4)	Currently in use at NRAO
B(1-1)	With Gerald Kuiper at University of Arizona
B(2-2)	Spare in Lab at NRAO

*A calibration curve is included for this hygrometer.

COMPARISON COMPILATION $\frac{mm}{AM}$ (Cont.)

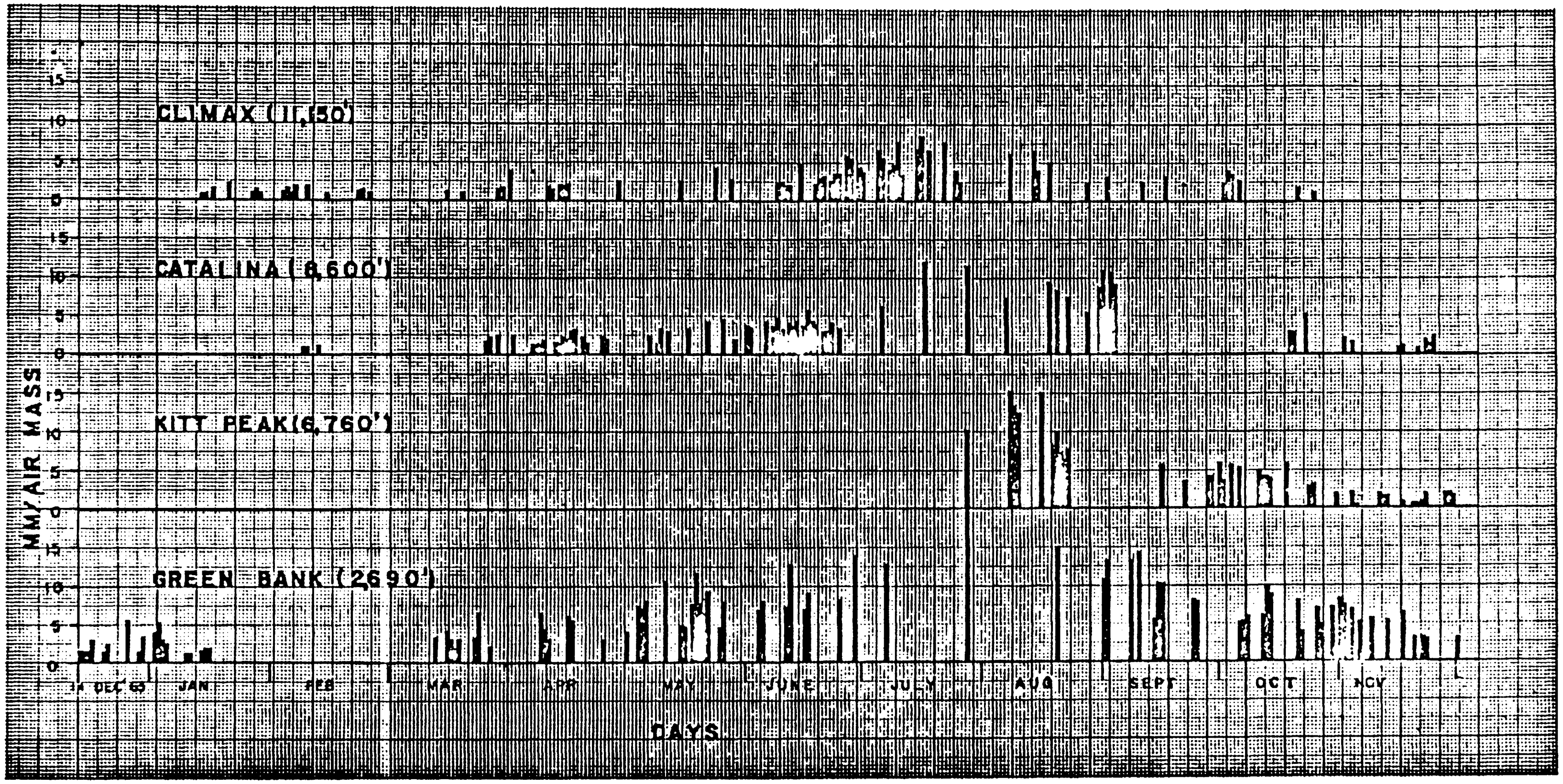
Month	Day	Green Bank	Climax	Kitt Peak	Catalina	Table Mtn.	Mt. Pinos	JPL
March	19	2.99						
	20		0.97					
	23	3.25						
	24	6.68						
	27	2.04			1.6			
	28				2.1			
	29		1.51					
	30		1.73		2.24			
April	1		3.86					
	2				2.40			
	7				1.33			
	8				1.33			
	9	6.53			1.29			
	10	4.41			1.70			
	11	3.09	1.82					
	12		1.49					
	13				1.50			
	14		2.02		1.40			
	15		1.94		2.20			
	16	6.11	2.13		2.00			
	17	5.51			2.95			
	18				3.2			
	20				2.1			
	21				1.4			
	25	3.00			2.1			
	26				1.8			
	29		2.48					
May	1	4.00						
	4	7.37						
	5	7.18						
	6	8.14						
	7				2.25			
	9				1.3			
	10				3.3			
	11	10.60						
	12				2.82			
	15	4.84	2.47					
	16	4.78						
	17				3.14			
	18	7.66						
	19	11.70						
	20	7.73						
	21	6.65						
	22	9.47			4.19			
	24		4.3					
	25	4.58						
	26	7.85						

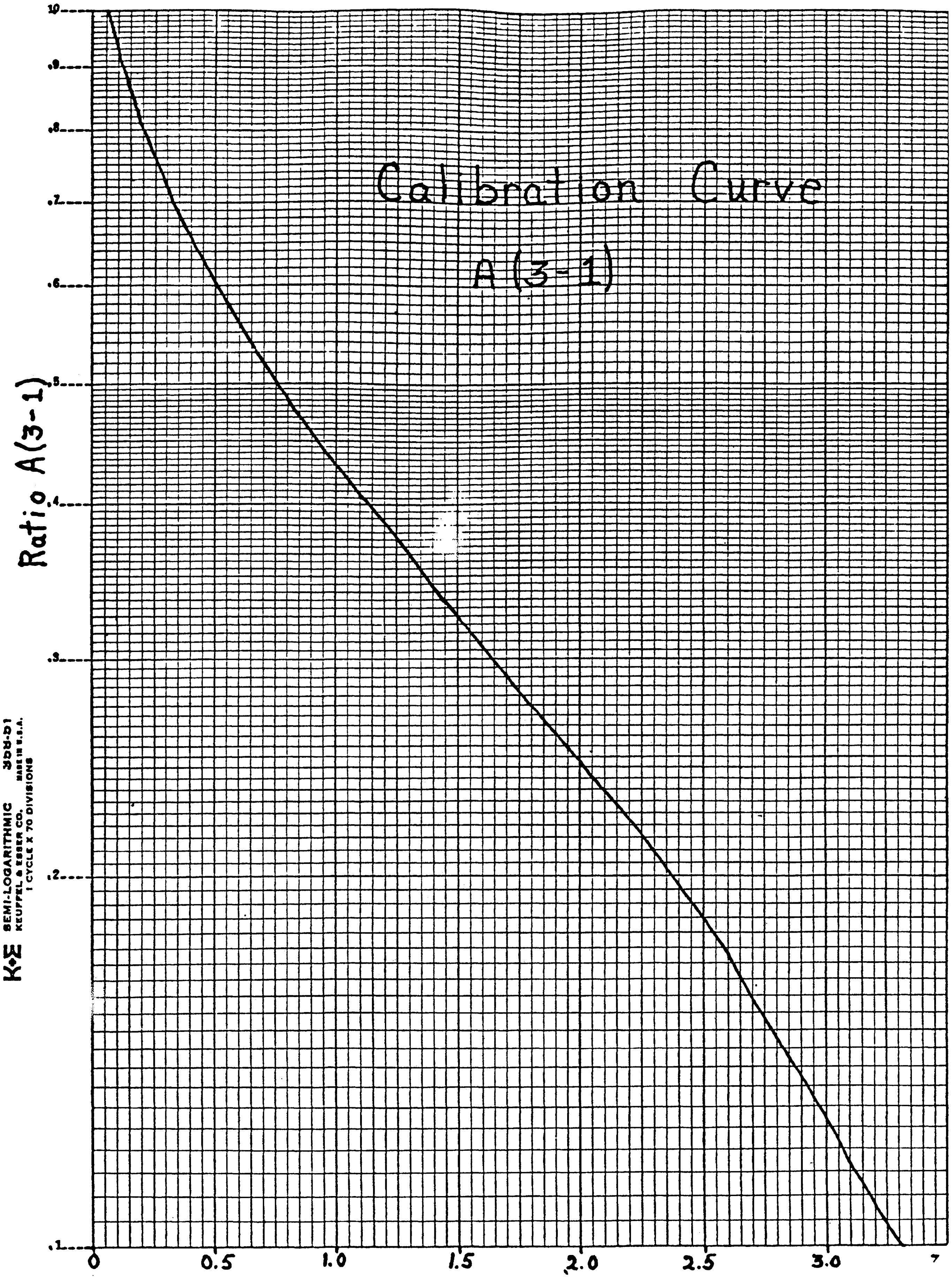
COMPARISON COMPILATION $\frac{mm}{AM}$ (Cont.)

Month	Day	Green Bank	Climax	Kitt Peak	Catalina	Table Mtn.	Mt. Pinos	JPL
May	28		2.88					
	29				1.93			
June	1				3.65			
	2				3.44			
	4	6.95						
	5	8.10						
	6				4.18			
	8				3.61			
	9		2.47		4.65			
	10		2.44		3.27			
	11	7.30	1.95					
	12	12.80	2.03		4.0			
	13				3.59			
	14				4.36			
	15		4.86		1.82			
	16	7.0			3.81			
	17	9.1			5.6			
	18				4.28			
	19		2.16		3.81			
	20		2.93					
	21		3.21		2.95			
	22				3.04			
	23		2.61		4.0			
	24		3.52					
	25	8.2	3.50		3.33			
	27		5.8					
	28		5.53					
	29	13.8						
	30		4.28					
July	1		3.74					
	5		6.62					
	6		5.50		6.14			
	7	12.8						
	8		4.08					
	9		4.81					
	10		7.76					
	11		3.40					
	15		6.71					
	16		8.46					
	17				12.0			
	18		6.60					
	22		7.59					
	25		3.67					
	26		2.41					
	28	23.5		10.2	11.5			

COMPARISON COMPILATION $\frac{\mathrm{mm}}{\mathrm{AM}}$ (Cont.)

Month	Day	Green Bank	Climax	Kitt Peak	Catalina	Table Mtn.	Mt. Pinos	JPL
Oct.	23				5.07			
	24			2.83				
	25			3.12				
	26	7.13						
	27	4.83						
	30	7.22						
	31			1.91				
Nov.	1	8.25						
	2	7.55			2.13			
	4	6.85		2.15	1.71			
	6	5.30						
	9	5.72						
	11			1.89				
	12			1.66				
	13	5.4		1.69				
	16				0.83			
	17	6.35		0.88	1.20			
	20	3.27		0.61				
	21			0.57	0.76			
	22	3.23		0.88				
	23	2.98		1.95	1.83			
	24				1.50			
	25				2.37			
	28			2.07				
	29			2.16				
	30			1.71				
Dec.	1	3.08						

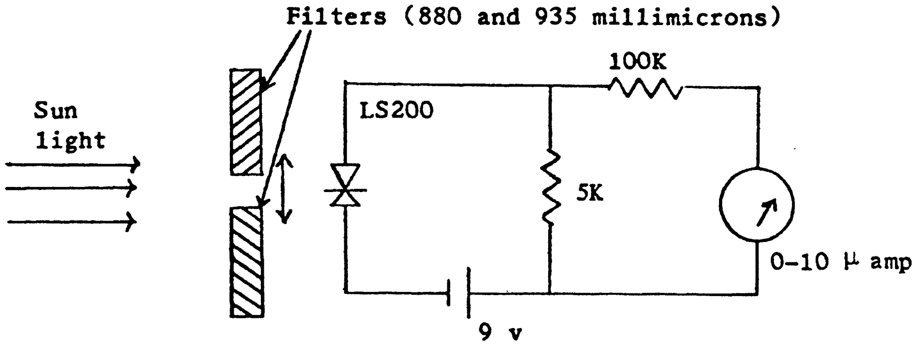

MM/AIR MASS
CLIMAX (11,150')
CATALINA (8,600')
KITT PEAK (6,760')
GREEN BANK (2,690')
15
10
5
0
14 DEC 65
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DAYS


Calibration Curve
A(3-1)
Ratio A(3-1)
10
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0.5
1.0
1.5
2.0
2.5
3.0
K+E SEMI-LOGARITHMIC 359-51
KEUFFEL & ESSER CO. MADE IN U.S.A.
1 CYCLE X 70 DIVISIONS

APPENDIX - The Portable Spectral Hygrometer

The basic principle is that developed by F. E. Fowle (Ap. J. 35, 149, 1912) and used by N. B. Foster, D. T. Volz and L. W. Foskett in their spectral hygrometer. Our design employs a single silicon diode to drive a resistive but rugged microammeter, thus yielding a highly portable hand held instrument. The spectral characteristics of the diode are the same as the silicon solar cell used in the Weather Bureau's instrument and the two filters are also essentially the same. The diode has excellent linearity and high output. Our calibration does not change noticeably with ambient temperature, and external power is not required. Except for differences in the linearity of the different types of detector, the NRAO instrument has a calibration curve similar to the Weather Bureau's instrument. This is quite helpful because it enables us to calibrate one of our instruments by comparison at the Weather Bureau in Washington with one of Mr. Volz's instruments.

The diagram shows the very simple circuit:



To make a reading the instrument is pointed at the sun with the 880 filter in front of diode. The meter will deflect nearly full scale. The reading should be carefully maximized and noted. With the 935 filter the deflection is somewhat less and depends strongly on the precipitable water vapor in the path. The ratio of the two readings is recorded along with either the time or solar zenith angle. An on-off switch is not required since negligible current flows when no sun light falls on the diode. The calibration curve gives the total water vapor in the path. This number is then reduced to units air-mass by means of the secant z formula.

Hygrometer A 3-1 was calibrated as follows: Fowle's data from absorption tube experiments was used to establish the shape of the curve at low water vapor levels. Comparison with Volz's instrument at higher levels provided an absolute reference since his instrument was empirically calibrated against radio sonde data. In addition A 3-1 was flown in a U-2 aircraft at Lockheed. After correcting on the ground for the effect of the airplane canopy, the reading at high altitude provided the zero point. We are indebted to both Mr. D. T. Volz of the U. S. Weather Bureau and to Lockheed Aircraft for their assistance.

NATIONAL RADIO ASTRONOMY OBSERVATORY
Green Bank, West Virginia

INTERNAL REPORT

MEASUREMENTS OF ATMOSPHERIC ATTENUATION AT 1 MILLIMETER AND A DESCRIPTION OF A PORTABLE SPECTRAL HYGROMETER

F. J. Low and A. W. Davidson

SEPTEMBER 1965

MEASUREMENTS OF ATMOSPHERIC ATTENUATION AT 1 MILLIMETER AND A DESCRIPTION OF A PORTABLE SPECTRAL HYGROMETER

F. J. Low and A. W. Davidson

SECTION I — ATMOSPHERIC ATTENUATION MEASUREMENTS

1. Introduction

This report presents the experimental results of an investigation of atmospheric attenuation in the 240-300 Gc (1-mm) radio window measured at Green Bank, W. Va., elevation 2600 feet. Previous workers indicated that the attenuation might vary by as much as 5-6 db with varying atmospheric conditions. Therefore, in order to investigate this problem and to provide accurate extinction data for reduction of astronomical measurements, a series of solar extinction curves were obtained in conjunction with the regular observing program. Section 1 of this report gives a brief description of the instrumentation, observational procedures, and the final results; section 2 gives a brief description of a spectral hygrometer developed in conjunction with the above program. This hygrometer has proven useful in surveys of possible sites for a large mm-wave telescope (NRAO Electronics Division Internal Report No. 31).

2. Instrumentation

The thermal detection radiometer (Low 1965) constructed at NRAO was used to collect the data. This system consisted of a 60-inch paraboloic reflector antenna, a 10 cps chopper, a waveguide feed horn, 1-mm bandpass filters, a germanium bolometer detector (Low 1965), a low frequency parametric amplifier (Biard 1962), a 10 cps amplifier-filter, a synchronous detector, and recorder. Figure 1 is a simplified diagram of the radiometer. When the antenna is directed at the sun the radiation is alternately passed and then blocked by the chopper wheel. This produces a square wave signal at the bolometer terminals which has an amplitude proportional to the brightness temperature difference between the sun and the back of the chopper wheel. When the antenna is pointed at nearby sky the signal is proportional to the difference between sky and chopper. The back of the chopper wheel is blackened to match the mean sky brightness. This square wave signal is amplified, filtered, and synchronously detected as shown in Figure 1. The output deflections are then recorded as a function of zenith angle and processed to obtain the atmospheric attenuation.

Since the bolometer is a linear power detector over a very wide dynamic range and the synchronous detector is a linear voltage detector, the output deflection is linearly related to the power received at the antenna.

3. Experimental Procedure

A standard observing procedure was developed and utilized throughout the program. This consisted of tracking a point in the sky near the sun and at predetermined intervals, alternately moving the antenna on and off the sun. This on-off procedure was repeated 5 times and constituted a set of measurements. Sets were taken at appropriate intervals throughout a half-day period and from this a solar extinction curve was generated. In addition, a known black body calibration source was introduced in front of the radiometer from time to time to provide a check of receiver gain stability. Finally, readings of elevation angle, temperature, barometric pressure, relative humidity, and total precipitable water were recorded, the latter being taken with the NRAO spectral hygrometer (see Section II for description).

4. Results

Figure 2 illustrates a typical half-day record. Each point represents the average of the five values in one set and is plotted against the appropriate air mass value. A best fit straight line is then drawn through the resulting points. The justification for equating air mass and secant zenith angle is that over the range of zenith angles we were able to observe (0 to 72 max.) the greatest error which could occur was on the order of 2 percent on the higher angles, and was therefore of small consequence.

After extrapolation of the resulting straight line back to zero air mass, the following procedure was used to calculate the total atmospheric attenuation:

1. Determine the receiver output at the 0, 1, 2, and 3 air mass ordinates.
2. Utilizing the formula

$$\Gamma = 10 \log \frac{V_{sun_1}}{V_{sun_2}}$$

where

Γ = attenuation in db/air mass,

V_{sun_1} = receiver output voltage at position 1,

V_{sun_2} = receiver output voltage at position 2,

the attenuation was then calculated using adjacent ordinate pairs (0-1, 1-2, 2-3).

As previously noted, a spectral hygrometer reading was also taken immediately after each set of radiometer determinations, and these were simply averaged over the half-day interval to arrive at a final figure.

A tabulation of the final results is given in Table 1. About 50 percent of the original data was not listed in this compilation for the following reasons:

(1) Any significant cloud cover may or may not produce added attenuation at 1 millimeter. This effect depends to a large extent on the type of cloud and its internal structure and at the present time has not been evaluated thoroughly.

(2) Some days, even though perfectly clear from a meteorological standpoint, displayed a marked deviation from a single best fit straight line at some point during the half-day interval. This generally happened in association with the passage of a frontal system. This phenomenon was also easily observed with the spectral hygrometer.

(3) Local ground fog was at times particularly severe at NRAO, persisting in some cases until well past local noon. The swiftly changing nature of this condition rendered these days data suspect.

In spite of the above, a large number of days yielded excellent data, with a very close grouping of the points about the best fit line.

Finally, Figure 3 shows a plot of attenuation in db per air mass versus precipitable water vapor in millimeters per air mass. The water vapor data were those obtained with the NRAO spectral hygrometer at the time of the attenuation measurements. This graph has proved very useful in predicting observing conditions without going to the trouble and time of setting up the 1 millimeter radiometer.

5. Conclusions

The data which are presented give the variation in attenuation over the entire 1-mm window for the driest conditions at Green Bank. The effects of clouds and ground fog have been purposely avoided. A good general survey of the distribution of water vapor as a function of elevation, season and geographic location within the U.S. is contained in Weather Bureau Technical Paper No. 10, "Mean Precipitable Water in the United States." The present results clearly show the necessity of making 1-mm observations from a dry site.

TABLE 1

COMPILATION OF ATTENUATION DATA

Date	Attenuation db/air mass	Water Vapor mm/air mass	Remarks
7/7/64	8.4	13.5	Very light haze
9/15/64	4.3	9.3	Very light haze
9/16/64	3.7	10.2	Clear
10/8/64	2.6	6.2	Clear
10/12/64	2.6	6.3	Clear
10/14/64	4.9	10.0	Very light haze
11/2/64	2.1	7.4	Clear
11/6/64	2.5	5.1	Clear
11/13/64	2.2	5.0	Clear
11/17/64	2.4	6.3	Clear
11/23/64	1.1	3.0	Clear
12/1/64	1.5	3.1	Clear
12/9/64	1.3	2.4	Clear
12/13/64	2.6	5.8	Clear
12/14/64	0.7	2.7	Clear
12/15/64	0.6	1.5	Clear
12/18/64	0.4	1.4	Clear
12/29/64	2.0	6.5	Clear
12/31/64	1.4	3.2	Clear
1/11/65	1.5	3.2	Clear
1/14/65	1.1	1.9	Clear
1/15/65	1.5	4.9	20 percent cloud cover
1/17/65	1.8	4.5	Clear
1/19/65	2.1	5.1	Clear
1/23/65	1.6	4.6	Clear
1/25/65	1.8	4.7	Clear
2/3/65	1.1	1.8	Very light haze
2/4/65	0.8	1.9	Clear
2/5/65	0.35	1.4	Clear
2/15/65	1.2	3.2	Clear
2/24/65	2.4	5.6	Clear
2/27/65	1.8	6.1	Clear
3/1/65	2.7	6.7	Clear
3/14/65	2.9	7.6	Clear
3/30/65	2.4	6.1	Clear
3/31/65	3.8	8.4	Clear
4/28/65	4.0	9.3	Clear
5/4/65	6.1	11.4	Clear

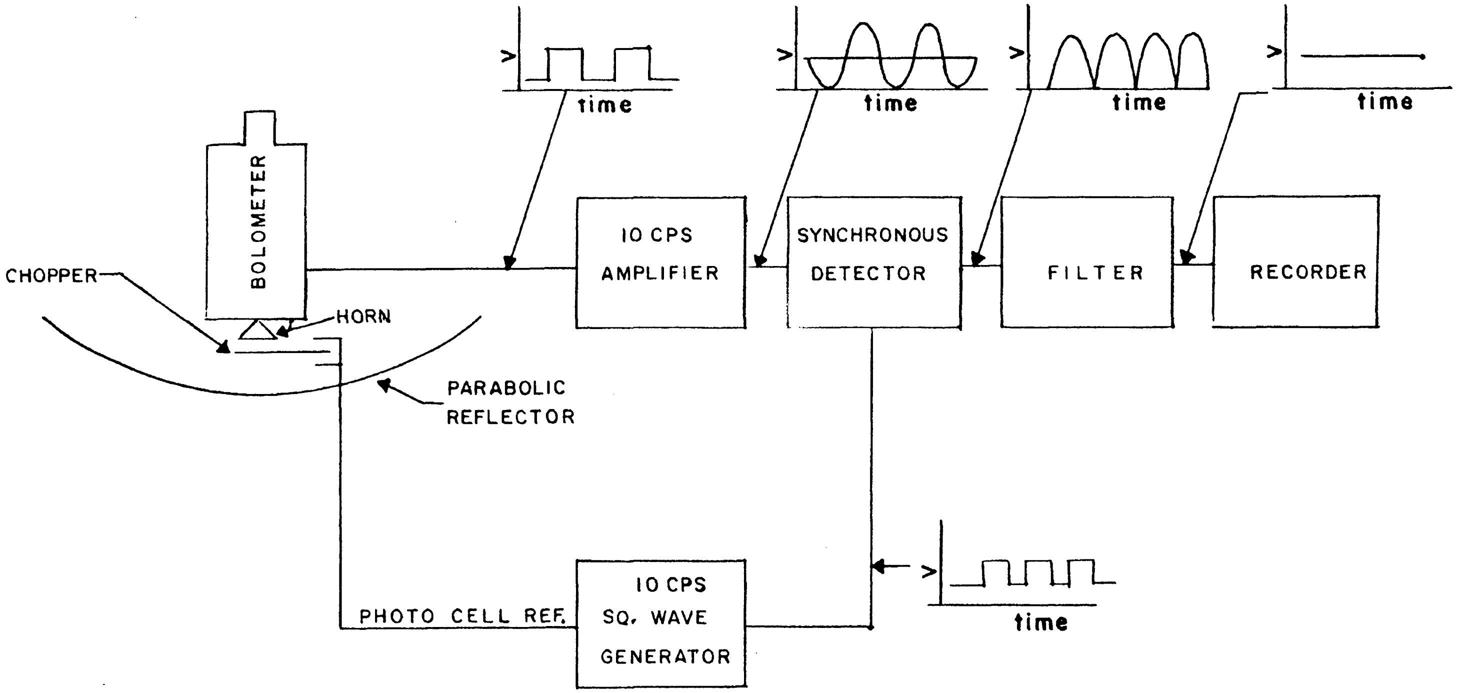
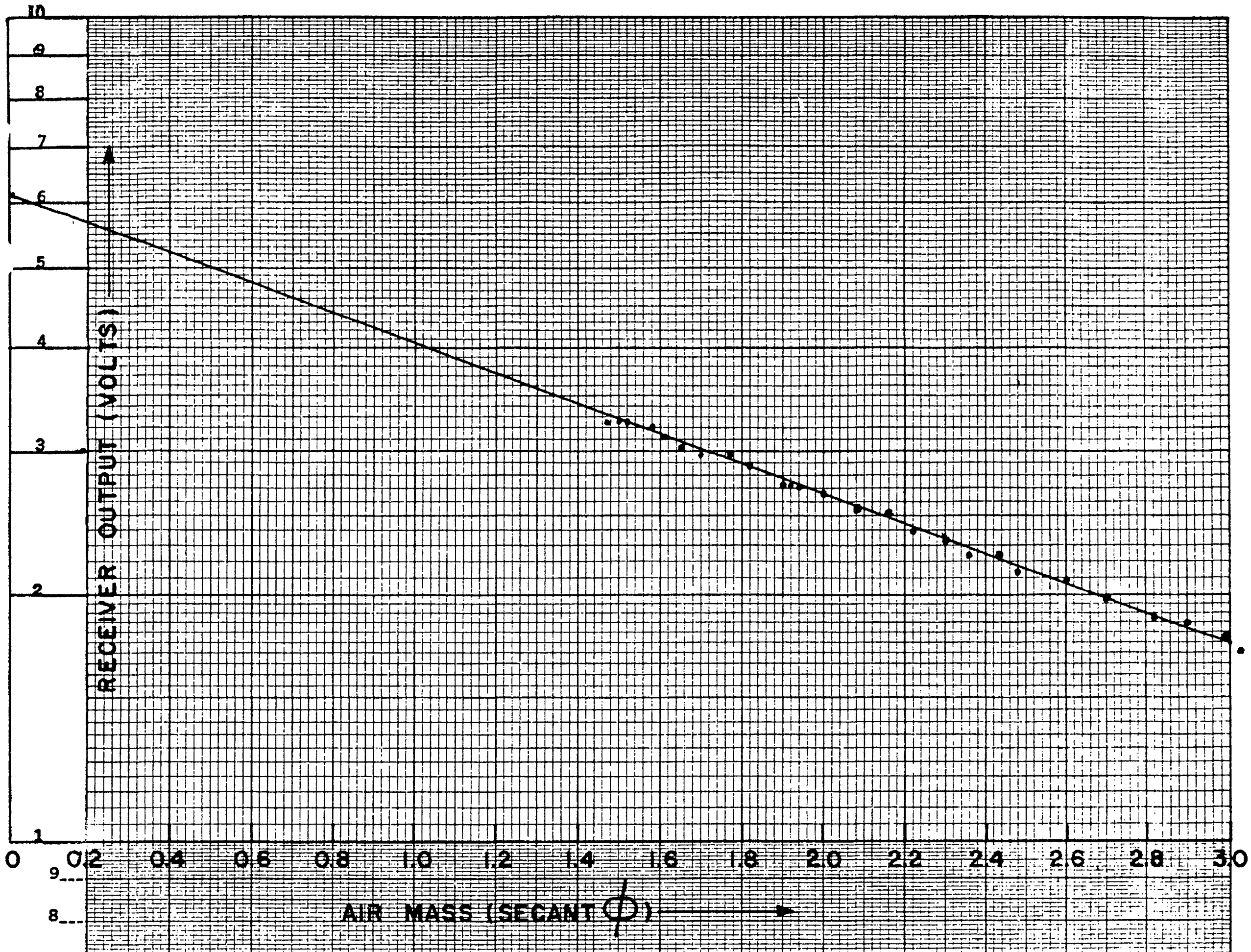


FIG. I BLOCK DIAGRAM I-MM RADIOMETER



0 a.m.	1 a.m	2 a.m	3 a.m	0-1	1-2	2-3	AVG. db/am	H_2O am
6.10	4.00	2.63	1.75	1.84	1.82	1.83	1.83	6.10

DATE - 2-27-65

TEMP. - 54°- 50°F

SKY - CLEAR

SOURCE - SUN

H_2O	
TIME	READ.
1205	6.3
1240	6.2
1304	6.1
1321	6.1
1342	6.0
1359	6.0
1426	5.8
1448	6.1
1506	6.2
1521	6.2
1536	6.1
1554	6.1
AVG.	6.1

FIG. 2 - SOLAR ATTENUATION

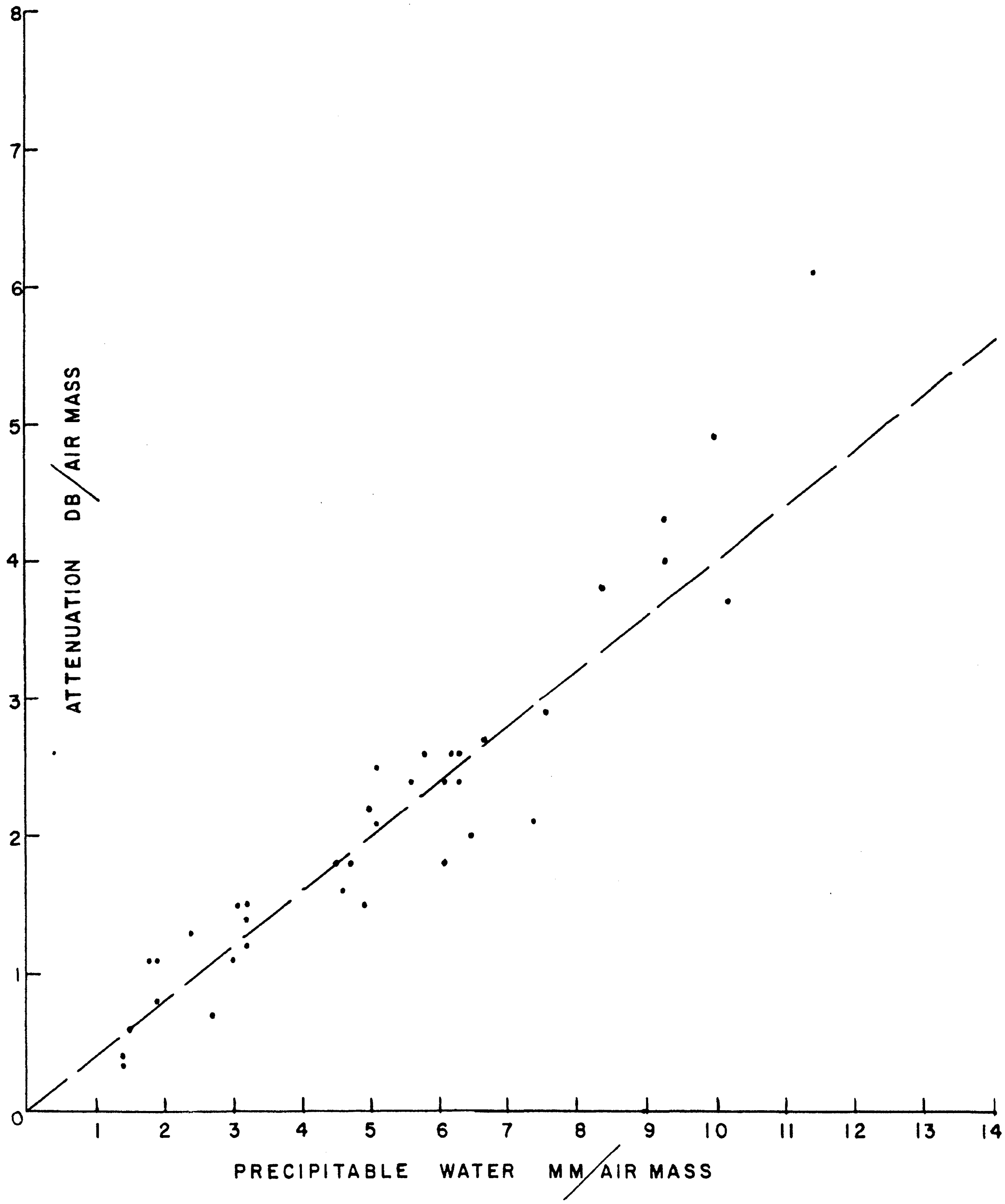


FIG. 3 ATMOSPHERIC ATTENUATION AT 1-MM

SECTION II — THE SPECTRAL HYGROMETER

1. General

Early in the 1 millimeter observing program, a need developed for a simple hygrometer for measuring the amount of water vapor in a vertical column of the atmosphere. This instrument would serve the dual purpose of allowing quantitative estimates of the observing conditions to be made prior to setting up the 1 millimeter radiometer, and also would provide a means of conducing site surveys for future millimeter telescopes. The U. S. Weather Bureau had developed a recording spectral hygrometer (Foster, Volz, Foskett, 1963) based on a technique first described by Fowle (Ap.J. 1912). Our portable instrument is based on these previous workers' results with some modifications and further refinements. This task was undertaken, and by late 1963 essentially complete. The following sections give the more pertinent details along with an evaluation of the results obtained.

2. Instrument Description

a. Theory — Figure 1 shows an outline drawing of the spectral hygrometer. Basically, the instrument compares the relative intensity of direct solar energy transmitted in a water-vapor absorption band against that of a nearby spectral region having essentially no absorption. For reasons stated in Volz's manuscript, the region of absorption is centered at 0.935 microns and the reference region at 0.880 microns. Narrow band-pass interference filters isolate the two spectral regions, and a photodiode is used as a radiation sensor. The instrument is so designed that the ratio of the photocurrents is proportional to the ratio of the transmitted radiant energies; this ratio is an index of the amount of water vapor in the sensing path using an empirically determined calibration curve. The latter quantity can then be divided by the solar air mass in order to obtain the vertical atmospheric water-vapor content or total precipitable water. Since pressure broadening of the absorption lines making up the 0.935 μ band affects the transmission thru the band, this type of instrument is subject to errors from varying height distributions of water vapor.

b. Optical components — Incident sunlight falling on the entrance slit first passes through a Corning sharp cutoff red filter (type C. S. No. 2-61 - transmittance < 0.5 percent at wavelengths below $0.590\ \mu$) which serves as both protection from the weather as well as to prevent the transmission of radiation through possible passbands of higher order. It next passes through one of the two first order, narrow-band-pass interference filters, whose characteristics are shown in the spectrophotometric curves of Figures 2 and 3. Note that the 880 mμ filter shows a transmittance of about 62 percent in the desired region, and only 4.6 and 4.3 percent in the unwanted regions of 1.1 μ and 2.0 to 2.3 μ. However, the 935, in addition to its peak at 935 μm, has peaks of 0.3 percent at 720 μm, 1 percent at 770 μm, 70 percent at 1.8 μ, 78 percent at 1.35 μ, 78 percent at 1.62 μ, and 73 percent at 1.97 μ, together with broad transmittance between 1.1 and 2.6 μ.

c. Photodiode — This unwanted radiation falling outside the pass-band is essentially eliminated, however, by the response curve of the photodiode which is shown in Figure 4. This device is a Texas Instruments Type LS-400, NPN silicon planar photodiode (TI Appl. Note 1962) which exhibits excellent sensitivity, temperature stability, and linear response. A careful calculation of the responses outside the pass-band yields an error of about 2 percent due to unwanted radiation for both filters, which was small enough to be neglected.

The remainder of the circuit is quite straightforward; the 9 V battery supplies bias for the photodiode, R_1 and R_2 are scaling resistors, and the meter is a highly sensitive 0-10 μA taut-band type. An on-off switch is not needed since the dark current is less than 10^{-7} amp.

d. Calibration — The calibration curve for hygrometer A3-1 is shown in Figure 5. The ratio as determined by the instrument is plotted along the Y axis; precipitable water vapor (x in cm) is shown along the X axis. This curve was established in the following manner: Fowle's data from absorption tube experiments were used to established the shape of the curve at low water vapor levels. Comparison with Volz's instrument at the U. S. Weather Bureau in Washington at higher water vapor levels provided an absolute reference since his instrument had been empirically calibrated against radiosonde data. In addition, A3-1 was flown in a U-2 aircraft at Lockheed Aircraft Company. After correcting on the ground for the effect of the airplane canopy, the reading at high altitude provided the zero point. Finally, duplicate instruments constructed at NRAO were then calibrated against A3-1. A check of the long-term stability of A3-1 was made after a 1 1/2 year period of almost constant use by flying again in a U-2 aircraft (courtesy of Davis-Monthan Air Force Base, Tucson, Arizona).

3. Evaluation

The instrument's operation, both in the laboratory and in the field, has demonstrated its dependability and relative accuracy. Changes in total precipitable water as detected by the spectral hygrometer were quite consistently comparable to those changes indicated by the 1 millimeter radiometer. Further tests have shown that the accuracy is not degraded by ambient temperature variations or by intensity fluctuation of the incident radiation. This feature is quite important for a portable instrument and is possible only because of the linearity of the photodiode.

Unfortunately, we have not found a simpler method of calibration or a method of transferring the calibration of A3-1 to other instruments except by the time consuming process of inter comparison. This has restricted the widespread use of the instrument.

4. Acknowledgements

The authors wish to express their appreciation to Messrs. Frank Bash, Wade Poteet and Ellis Remsberg for their assistance in the construction and testing of the hygrometer.

R1-100K
R2-5K
Note-R2 must be chosen for each diode filter combination to keep all deflections on scale.

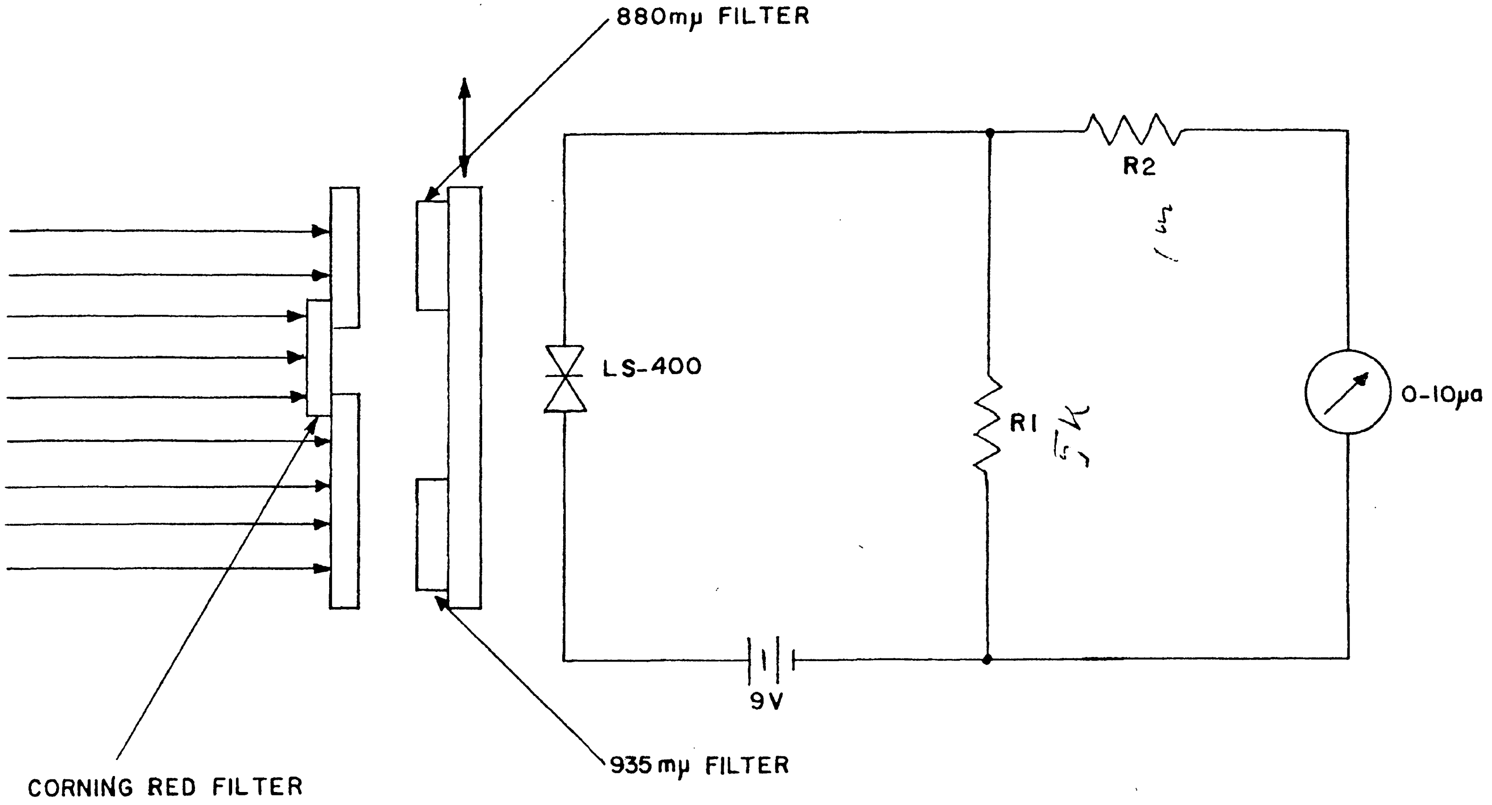


FIG. 1 OUTLINE DRAWING OF SPECTRAL HYGROMETER

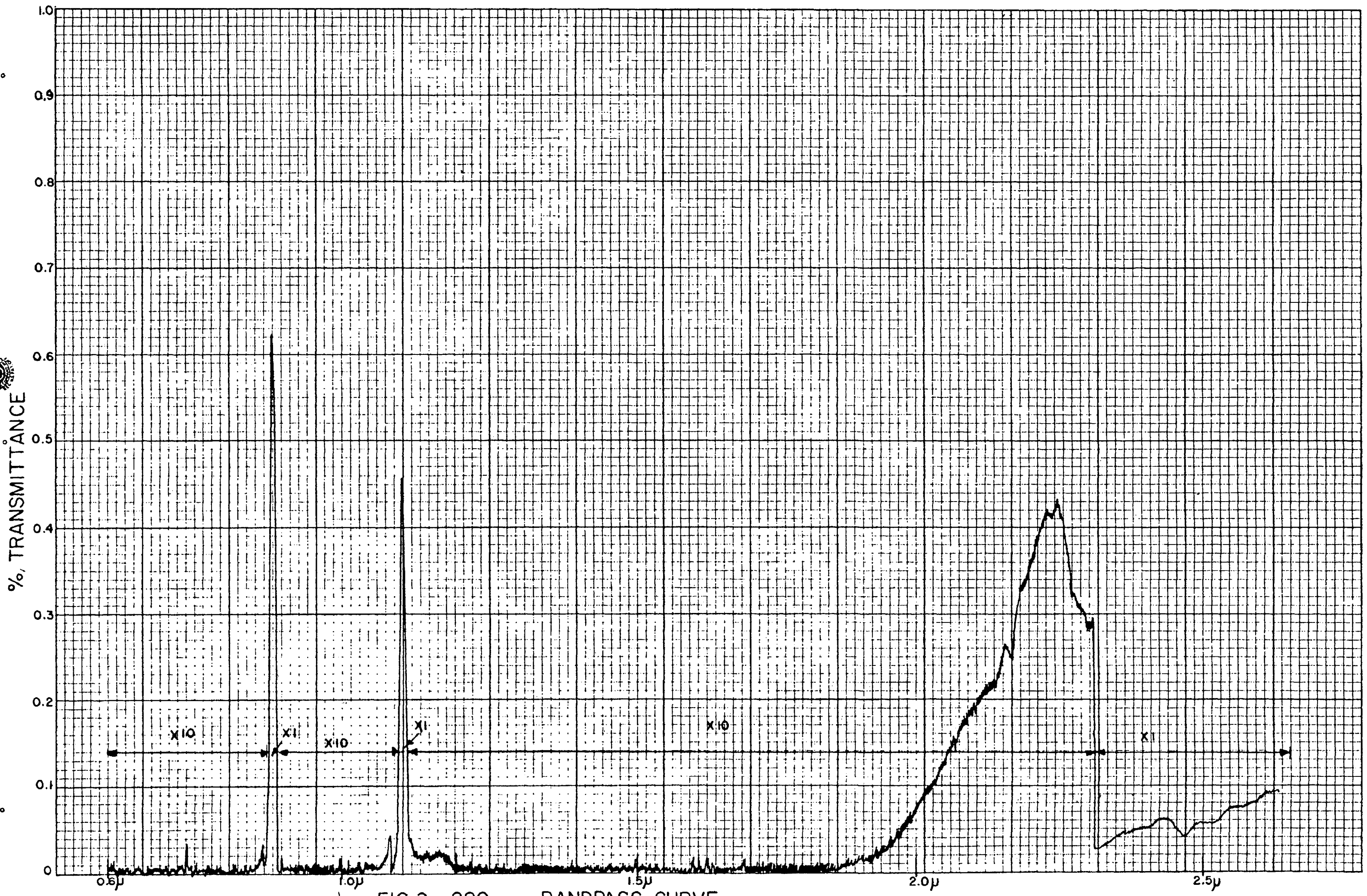


FIG. 2 - 880mμ BANDPASS CURVE

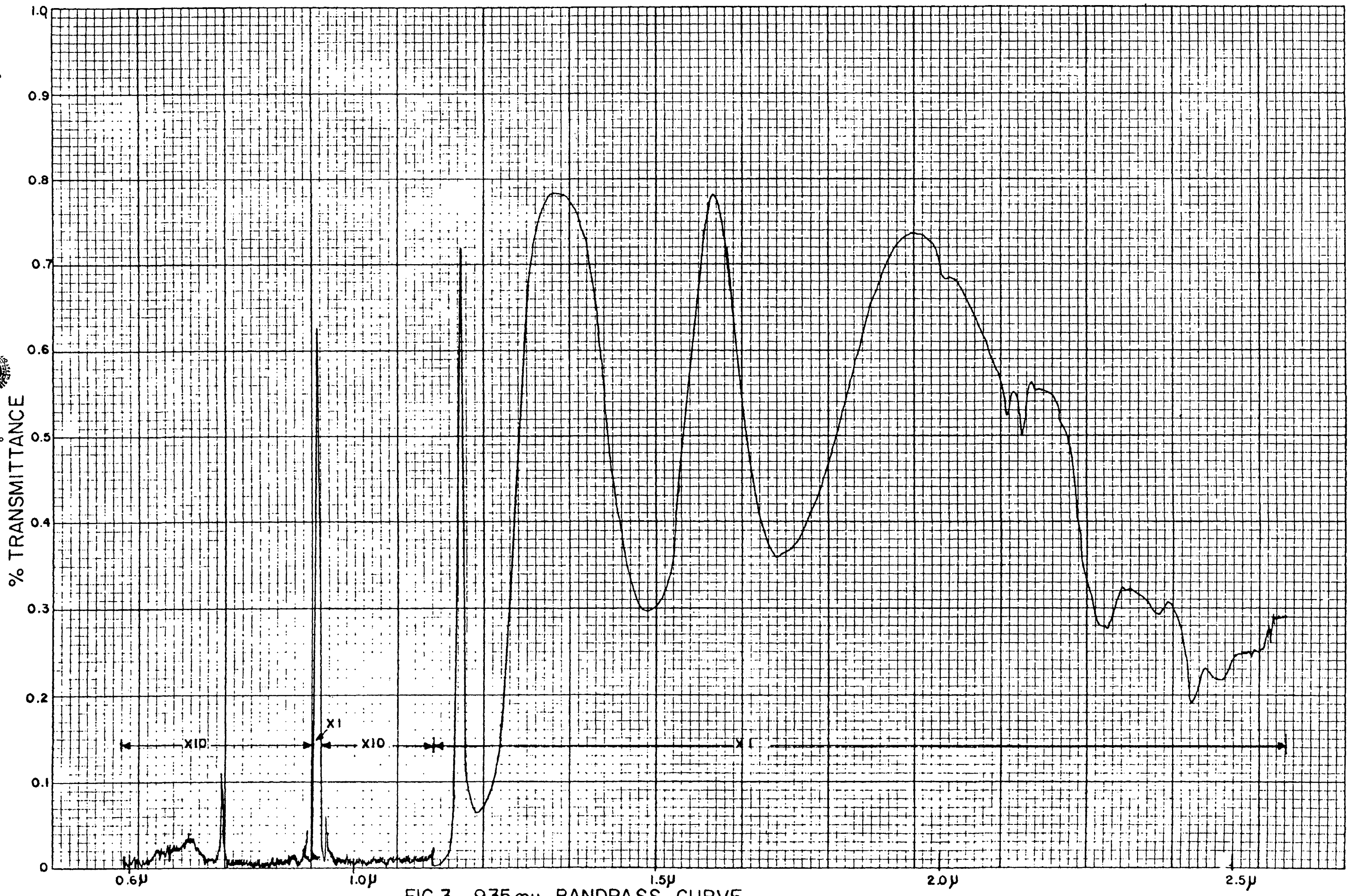


FIG. 3 - 935 mμ BANDPASS CURVE

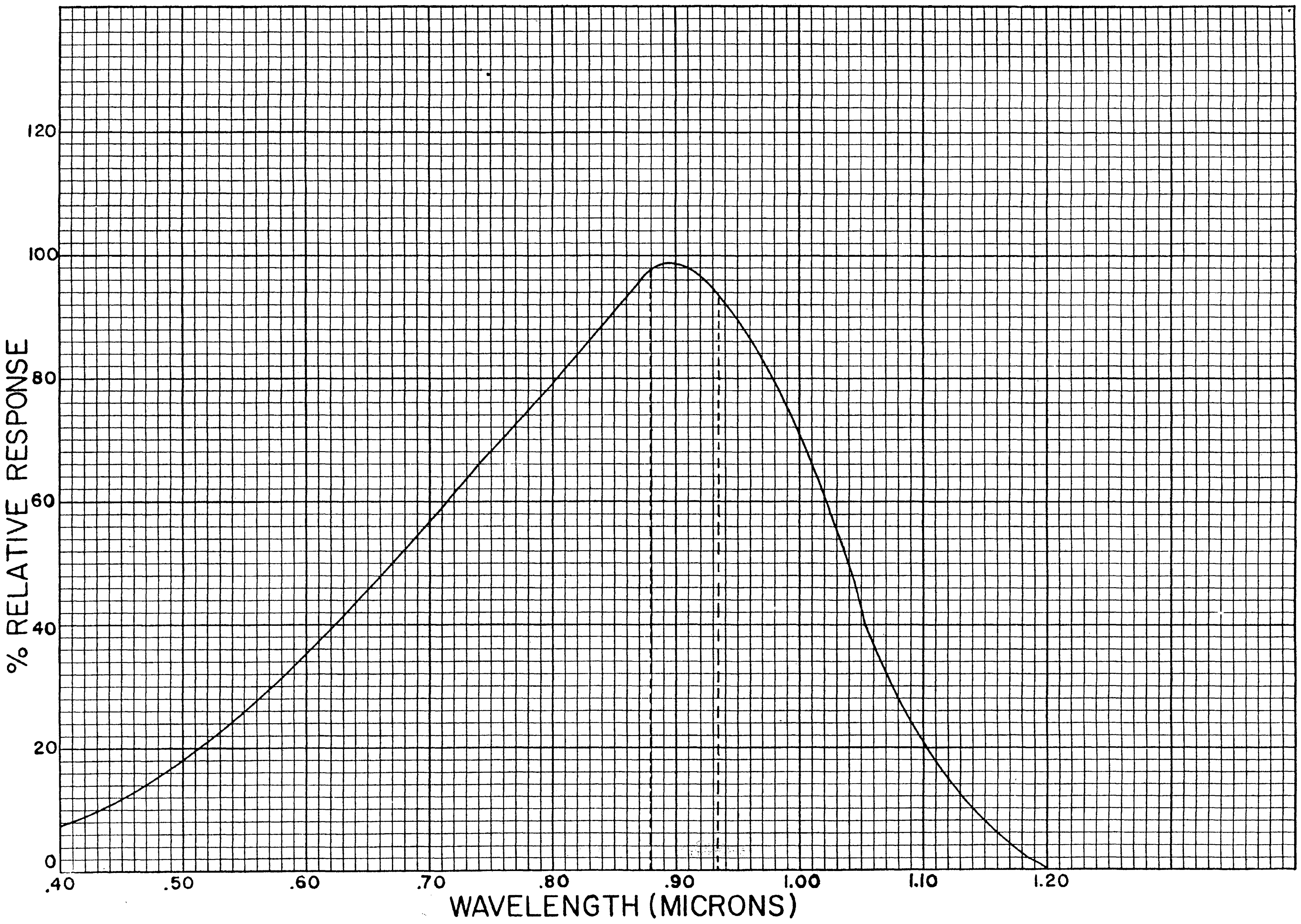
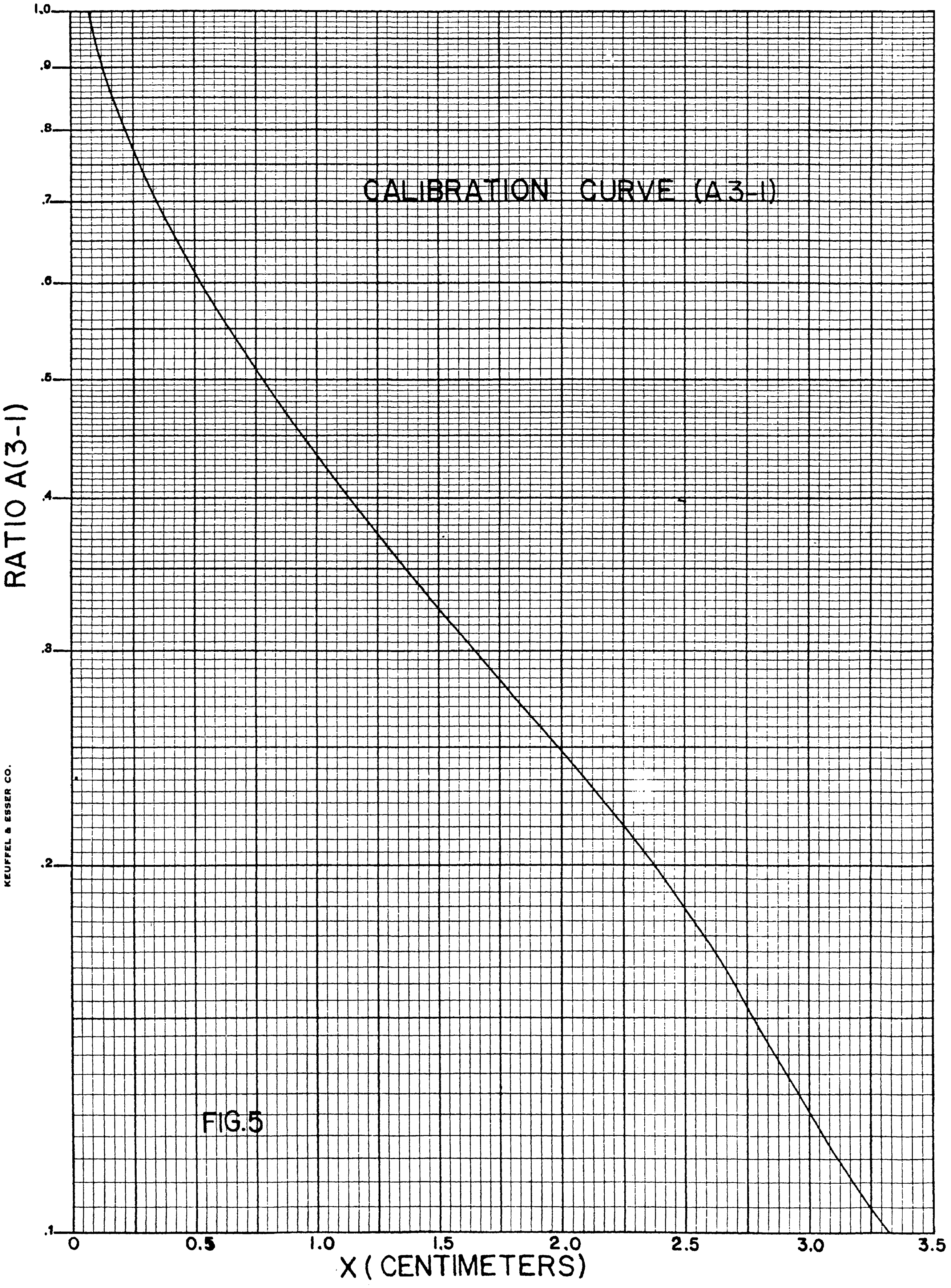


FIG. 4 LS-400 SPECTRAL RESPONSE CURVE



CALIBRATION CURVE (A3-I)

FIG.5

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CALIBRATION OF AN ATMOSPHERIC WATER VAPOR METER BY MEANS OF SYNTHETIC SPECTRA

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ABSTRACT

Calculations for the relative calibration curve of a two filter water vapor meter using the 1.9μ water vapor band are presented. The calculations show the sensitivity and general range of applicability of the meter. A layered atmospheric model gives the relationship of the calibration curve as a function of altitude.

I. Introduction

The severe absorptions by water vapor in our atmosphere have always been an obstacle for astrophysical observations in the infra-red. Astronomers have traditionally paid close attention to the monitoring of the total telluric water vapor along the observation path (Fowle 1912). Knowledge of the amount of water vapor is necessary for the correction of observations made at different zenith angles and is important for the selection of "dry" telescope sites for the infra-red.

This paper describes the calibration of a portable water vapor meter built under the direction of J. Westphal (1972) for the 1972 NASA infra-red site survey. ( ) The meter is basically a simple two-filter photometer. One filter has its maximum transmission in the center of the 1.9 μ telluric water vapor band, the other one in a wavelength region with no atmospheric absorptions (see Fig. 1). When the instrument is pointed at the sun, the ratio of the two filter intensities gives a measure of the total water vapor in the path.

The design of the meter is based on an earlier portable water vapor meter designed by F. J. Low, (F. J. Low and A. W. Davidson 1965, and <u>private communication</u> 1973) which utilized the weaker 0.935 μ water vapor band and a silicon detector. That instrument was in turn patterned after a "spectroscopic hygrometer" developed by Foster, Volz, and Foskett (1965) at the U. S. Weather Bureau also using the 0.935 μ water vapor band. A variety of instruments and methods to measure humidity by spectroscopic techniques are described under the subject of "spectral hygrometers" in the proceedings of the 1963 International Symposium on Humidity and Moisture (A. Wexler and R. E. Ruskin, ed., 1965).

One of the most difficult problems in the proper use of such a meter has always been its calibration. The absorption of an individual water vapor line depends not only on abundance but also on pressure and temperature. For a large number of water vapor lines with various intensities and different degrees of overlap, such as are contained within the bandpass of our filter, only approximate analytical models exist (Goody 1964). The problem becomes more severe for atmospheric slant path measurements where the abundance, pressure, and temperature vary along the absorbing path. All of these factors can, however, be properly taken into account by numerical calculations such as are made possible by modern high speed computers. We developed a spectrum synthesis program for the problem of water vapor in the Venus atmosphere (Fink et al. 1972). Only minor changes were necessary to make this program applicable to the present problem.

II. Analysis and Results

Total atmospheric absorption was calculated by summing up the contributions to the absorption coefficients from a number of individual layers. For each layer the absorption coefficient was calculated at discrete grid points, spaced on a linear wavenumber scale. At each grid point, the absorption coefficient was obtained by summing the individual absorption coefficients from all lines making a significant contribution. Each line was calculated using a Lorentz profile and line parameters from the 1.9μ water vapor band which were published by Benedict and Calfee (1967). The atmospheric transmission was then computed by taking the natural exponential function of the total absorption coefficient. The transmission through the filter resulted from the multiplication of the synthetic water spectrum by the measured filter curve shown in Fig. 1.

Examples of the calculated filter transmission for a single layer with various amounts of water vapor are shown in Fig. 2.

In principle the above calculations can be carried out with a high degree of accuracy with the large computers that are now available. In our calculations we used a somewhat smaller machine, an IBM 1130, which necessitated certain limitations in the numerical approximation to the physical situation. Two restrictions affected the accuracy of the data. First, not all the lines listed in Benedict and Calfee within our filter passband were used in our calculations. The most intense lines in their compilation of the 1.9μ water vapor band have an intensity of ca. 1000 cm^{-1}/gm cm^{-2} . We restricted ourselves to the 475 lines stronger than 1.0 cm^{-1}/gm cm^{-2} . An estimate, supported by test calculations, showed that the remaining lines could contribute at most 0.5% to the absorption. Secondly, since the line profile was limited to 800 grid points, a compromise had to be made between faithful reproduction of the line center and the extent of the Lorentz wings. Most calculations were carried out with a grid point spacing such that the wings were cut off 40 cm^{-1} from the line center. Calculations with different spacings for weak and strong absorptions showed that the maximum error incurred by this approximation was about 1%. Since the accuracy of the input parameters from Benedict and Calfee is of the order of 5-10%, we feel that the latter uncertainty sets the limit to the accuracy of our results.

To establish a calibration curve, the remaining transmission of the filter (see Fig. 2) was integrated to give the total absorption in wavenumbers. This can be converted to a percentage of the clear transmission of the filter by using the value of 72.0 cm^{-1} for the area under the filter with no absorption. We show in Fig. 3 a calibration curve for a single layer at a temperature of 295 °K, a pressure of 1.0 atm, and varying abundance. The curve differs only slightly from the multilayer calculation discussed below. The general characteristics of this particular meter can be seen immediately. The meter is most sensitive for precipitable water vapor abundances of 0.005 to 1.0 mm. Even for the low abundance of 0.010 mm found, for example, in our atmosphere above the level of the tropopause (near 12 Km), there is considerable absorption left.

We wish to point out that our calculations give, of course, only a relative calibration of the meter. To put this calibration on an absolute basis the area of the comparison filter, solar energy distribution, detector response, together with any other known instrumental factors must be taken into account. Although these effects can be accounted for, theoretically it is often simpler and more reliable in practice to put the calculated curve on an absolute basis by actual measurement through the atmosphere with the concentration of water vapor known, e.g. from radiosonde data. The presence of Paschen α (18751 Å, equivalent width approximately 1.6 cm^{-1} (Bijl, Kuiper and Cruikshank, 1969)) and other solar lines within the filter passband will reduce the clear filter transmission with no water vapor present below its calculated 72.0 cm^{-1}. Variability of these lines should be negligible. Since no region in the infra-red is completely free from water vapor absorption, we checked the absorption produced in the reference filter passband at 1.64 μ by the 355 lines listed for that region by Benedict and Calfee. With an abundance of 10 mm precipitable water vapor, less than 1% absorption was produced so that this source of error can be neglected.

It was realized even in the earliest atmospheric water vapor measurements (Fowle 1912) that the varying temperature and pressure along the absorbing path can affect the results significantly. It is in this area that synthetic spectrum calculations are most useful. Laboratory measurements can provide data for fixed temperature and pressure, but not for inhomogeneous distributions such as exist in our atmosphere. Once molecular parameters are established in the laboratory for different temperatures and pressures, however, they can then be used to calculate the spectrum of any inhomogeneous distribution.

We first investigated the effects of temperature and pressure in a single layer. For abundances of both 0.010 mm and 1.0 mm and a constant pressure of 1 atm it was found that a variation in temperature from 200°K to 300°K changed the absorption by less than 5%. However, changing the pressure from 0.2 to 1.0 atm at a constant temperature of 295°K changed the absorption from 4.0 to 5.0 cm^{-1} at 0.010 mm abundance and from 30.5 to 49.0 cm^{-1} at 1.0 mm abundance. The general features of this result were not unexpected, but the exact numbers could only be obtained by numerical calculation. In the Ladenburg and Reiche curve of growth the absorption of a strong line depends on the product of the pressure and the abundance, through the mechanism of pressure broadening. For weak lines, or low abundance, the curve of growth shows a linear increase with abundance. The weaker dependence on the temperature is caused by the changing populations of the absorbing energy levels.

An inhomogeneous layered atmosphere was constructed using the parameters shown in Table I. It can be seen in Table I that the water vapor falls off very rapidly with altitude and for the present calibration can be neglected above 12 Km. The mean mid-latitude water vapor profile suggested by Sissenwine (1968), which is based on balloon observations, agrees very well with a water vapor scale height of 2.3 Km, except near the tropopause. The results of the calculation are shown in Fig. 4. The calibration curve as a function of altitude and the layers in Table I were chosen to coincide with the altitude of typical existing observatories (Mt. Palomar (Calif.) 1706 m, Kitt Peak (Ariz.) 2064 m, McDonald (Texas) 2081 m) and with altitudes of typical proposed sites (Mauna Kea (Hawaii) 4215 m, White Mtn. (Calif.) 4344 m, San Francisco Peaks (Ariz.) 3852 m). The calibration curve in Fig. 4 was limited to abundances expected for such locations. The figure shows that because of pressure effects the water vapor at the higher altitude is underestimated if a sea level calibration curve is used. If a new meter is to be calibrated against an existing meter the calibration must be done at the same altitude at which the original meter was calibrated. For purposes of determining site suitability for infra-red observations, however, the total absorption should be used since it is a direct measure of the atmospheric opacity including pressure effects, although it is not a measure of the atmospheric water vapor.

Since the atmospheric water vapor varies considerably from day to day a number of models were investigated which deviated from the mean in Table I. In particular, the Northern Hemisphere Atmospheric Humidity Atlas (Gringorton, 1966), which gives humidity as a function of altitude, was used to construct deviant models for specific locations (White Mtn, Calif., Mauna Kea, Hawaii, Mt. Lemmon, Ariz.). None of these models differed by more than 1% from the results shown in Fig. 4. From this

We conclude that expected variations in the detailed distribution of water vapor do not change the calibration curve significantly.

Conclusion

We wish to emphasise that although the present calculation was carried out for a specific problem, the method of using synthetic spectra for the calibration of atmospheric transmission is of quite general application. The molecular parameters for most of the bands of our atmospheric constituents are well known, so that calculated spectra can be produced. With larger and faster computers the computational error can be made almost arbitrarily small so that the final accuracy of the results will depend on the precision of the input laboratory data. A single layer calculation can quickly show the sensitivity of a particular filter for various concentrations of atmospheric gasses. Optimum filter postions can then be chosen without costly experimental trials. A multilayer computation gives the calibration of the filter for any desired altitude and requires only one experimental point for absolute calibration. The method can also be applied to either localized or extended atmospheric pollutants provided that they show sufficiant absorptions.

Acknowledgments

Our special thanks goes to R. F. Poppen whose excellant programming produced our spectrum synthesis programs and who made the modifications necessary for the present calculations. This research was supported in part by NASA grants to Dr. G. P. Kuiper numbered NSG 161-61 and NG 2-03-002-002.

TABLE I: Parameters used for layered model atmosphere.

Layer Altitude Km	Av. Pressure Atm (a)	Av. Temp K (b)	Fractional distribution of water vapor (c) above 0 Km	(c) above 2 Km	(c) above 4 Km	(d) above 0 Km
0 - 2	0.883	289	0.584			.607
2 - 4	0.688	277	0.245	0.588		.257
4 - 6	~~0.5~~35 .535	265	0.103	.247	0.600	.095
6 - 8	0.417	253	0.043	.103	.250	.032
8 -10	0.324	241	0.018	.044	.106	.008
10 -12	0.253	229	0.008	0.018	0.045	.001

(a) using an atmospheric scale height of 8.0 Km.

(b) using a temperature gradient of -6°K/Km.

(c) using a scale height for water vapor of 2.3 Km.

(d) from the integrated results of Sissenwine (1968) for his suggested mean mid-latitude water vapor profile.

Figure Captions

Fig. 1 Transmission curves of the filter centered at 1.87μ in the 1.9μ water vapor band (A) and the reference filter centered at 1.64μ (B).

Fig. 2 Sample synthetic spectra within the filter band pass at a temperature of ~~295°K~~ 250°K and a pressure of 0.5 atm for various water vapor abundances.

Fig. 3 Calibration curve of filter absorption vs. water vapor abundance calculated for a single layer at a temperature of 295°K and a pressure of 1 atm.

Fig. 4 Calibration curve, based on the layered atmosphere listed in Table I, and showing the effect of altitude on the filter transmission.

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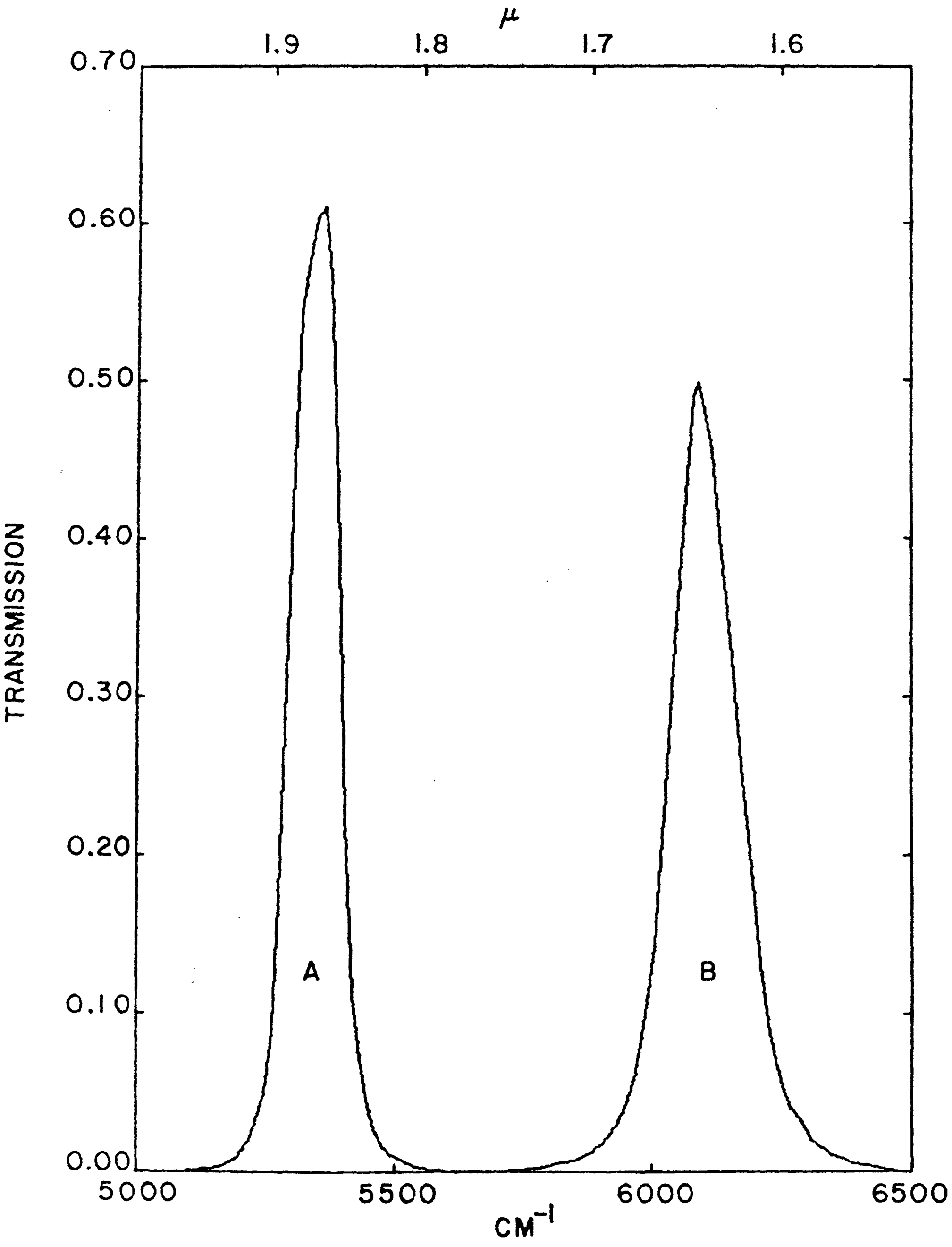


μ
1.9
1.8
1.7
1.6
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
TRANSMISSION
A
B
5000
5500
6000
6500
CM^{-1}

Fig. 1

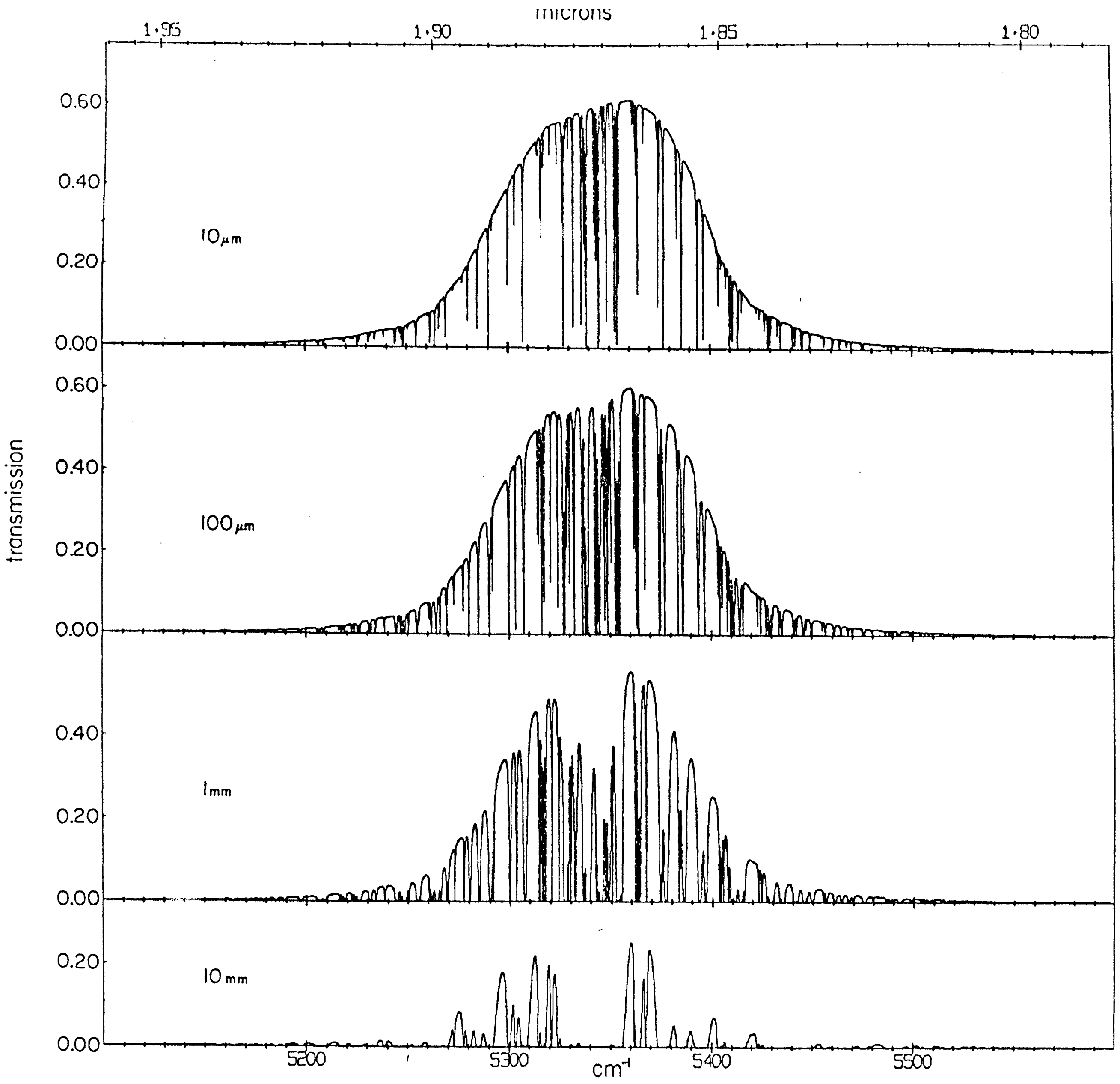

microns
1·95
1·90
1·85
1·80
transmission
0.60
0.40
0.20
0.00
10µm
100µm
1mm
10mm
5200
5300
5400
5500
cm⁻¹

Fig. 2

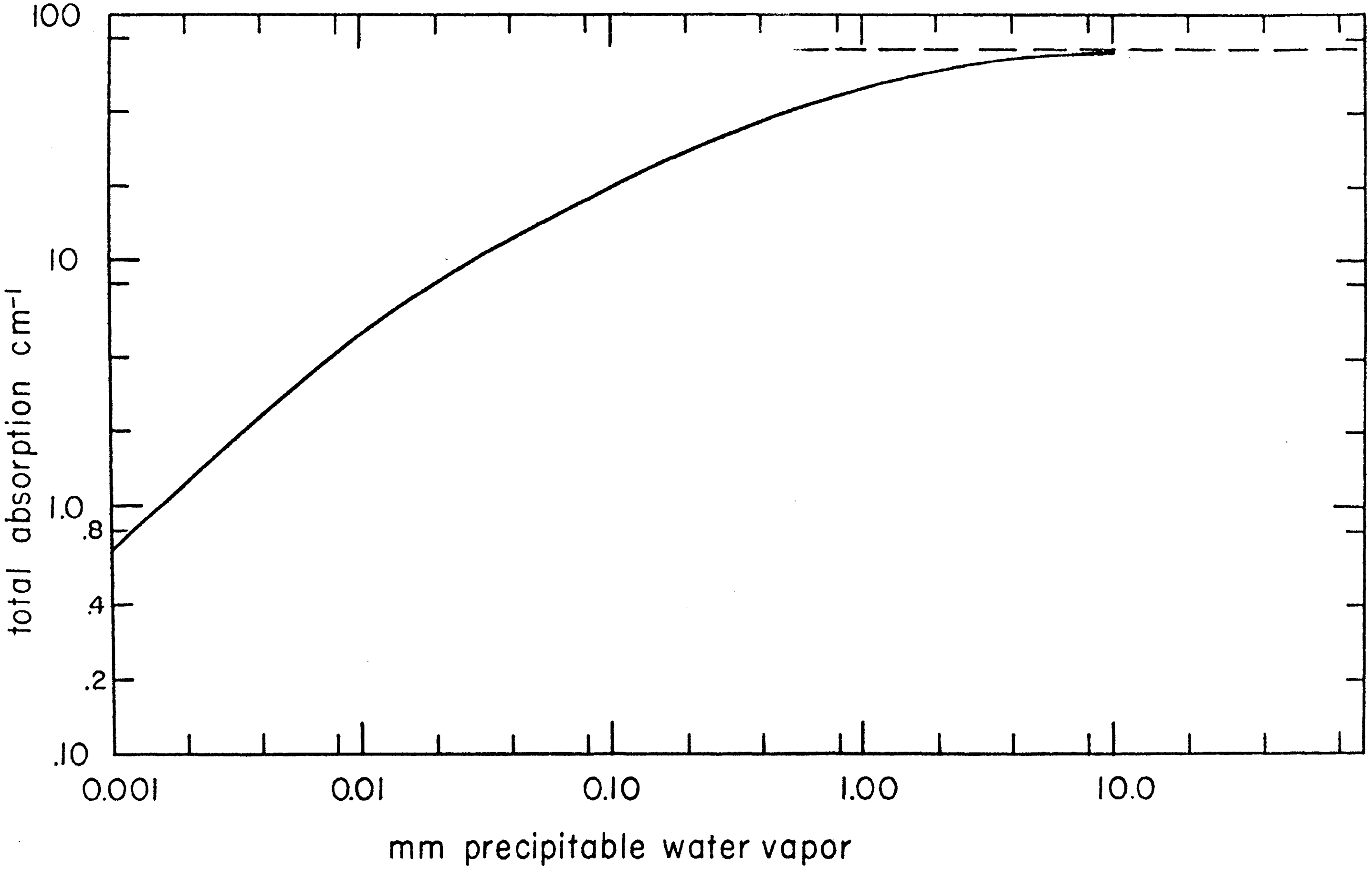
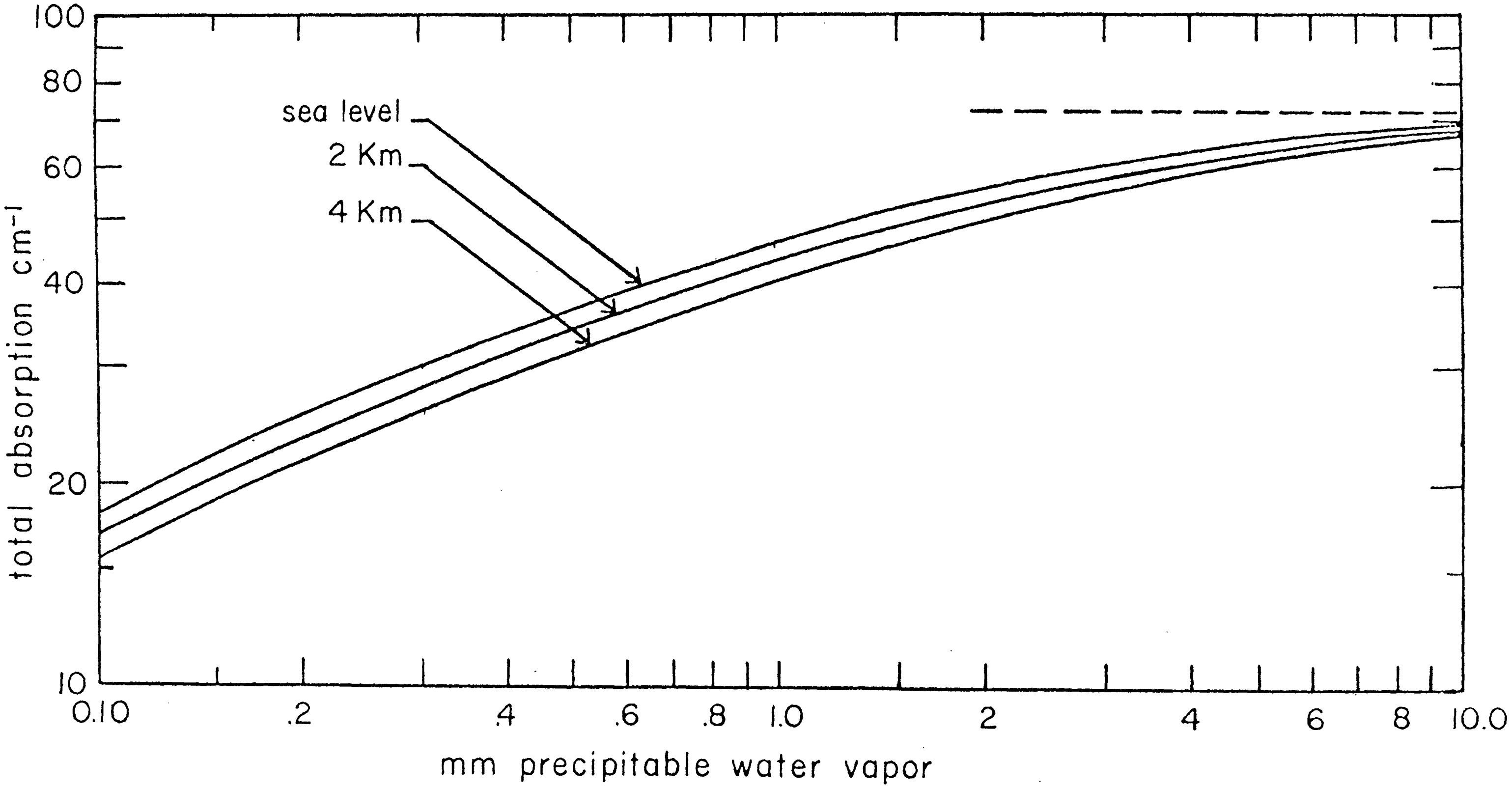

100
10
1.0
.8
.4
.2
.10
total absorption cm⁻¹
0.001
0.01
0.10
1.00
10.0
mm precipitable water vapor

Fig. 3



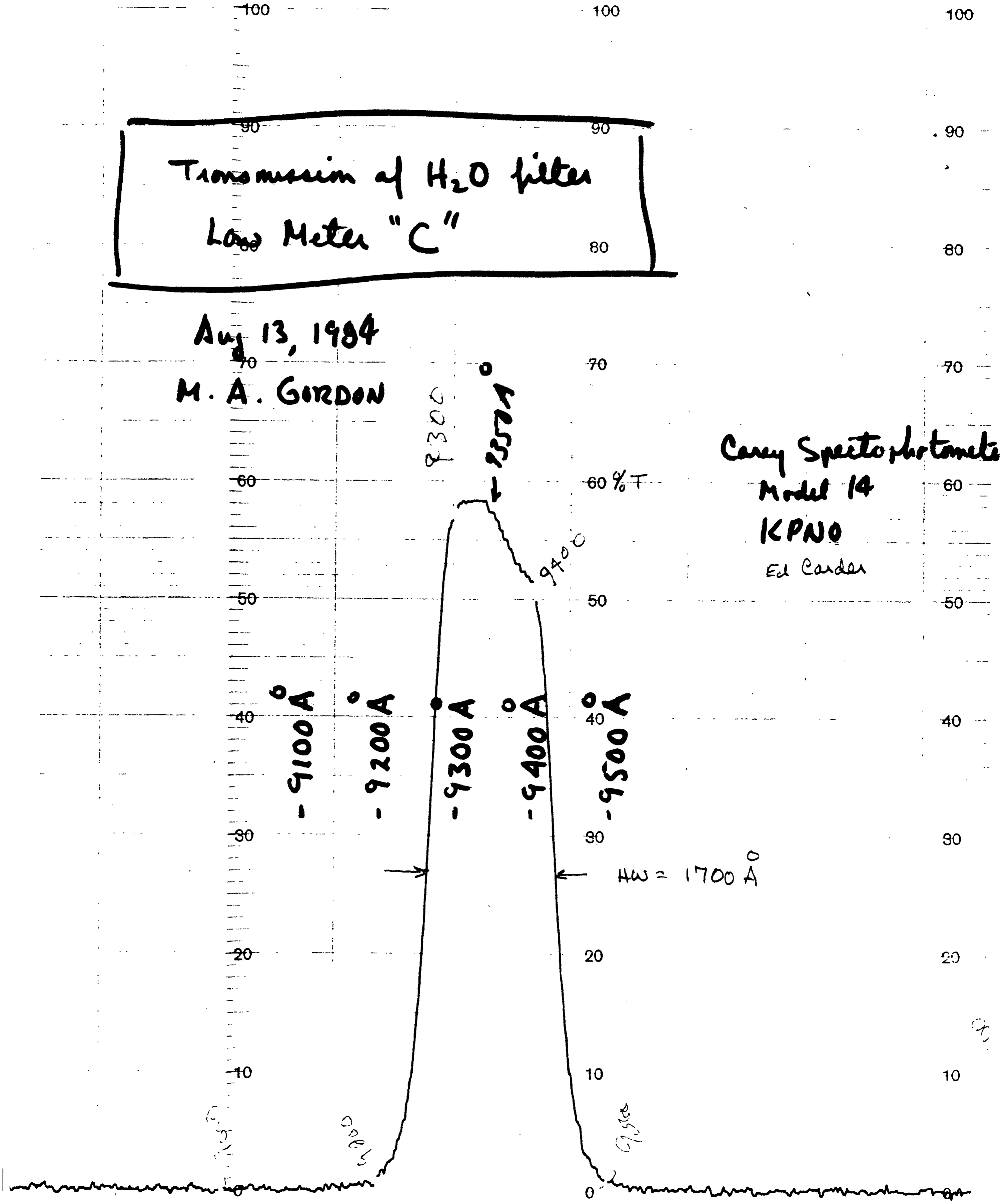
100
80
60
40
20
10
total absorption cm^{-1}
sea level
2 Km
4 Km
0.10
.2
.4
.6
.8
1.0
2
4
6
8
10.0
mm precipitable water vapor

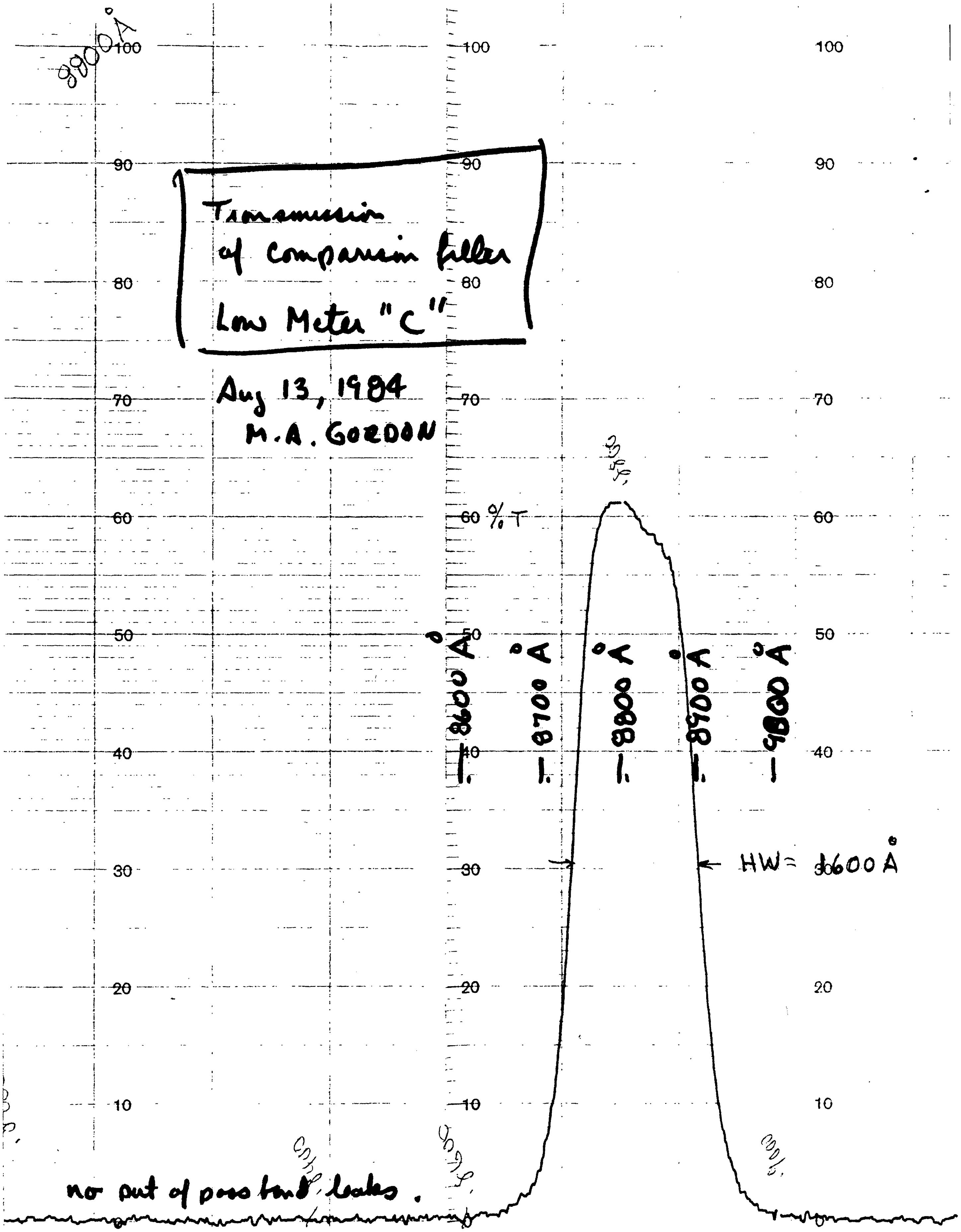
Transmission of H_2O filter Low Meter "C"

Aug 13, 1984

M. A. GORDON

Carey Spectophotometer
Model 14
KPNO
Ed Carder





Transmission
of Comparison filter
Low Meter "C"

Aug 13, 1984
M.A. GORDON

no out of pass band leaks.