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A SELECTIVE REVIEW OF GROUND BASED PASSIVE
MICROWAVE RADIOMETRIC PROBING OF THE ATMOSPHERE

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ABSTRACT

This article reviews past and current work on probing of the atmosphere by ground based passive microwave radiometers. The absorption of the various atmospheric constituents with significant microwave spectra is reviewed. Based on the available data, an estimate is made of the uncertainty in the microwave absorption coefficients of the major constituents, water vapor and oxygen. Then there is an examination of the integral equations which describe the three basic types of observations: measurement of the spectrum of absorption of the sun's radiation by an atmospheric constituent, measurement of the emission spectrum of a constituent, and measurement at one frequency of the zenith angle dependence of the absorption or emission of the atmosphere. The weighting functions or kernels for observations of ozone, water vapor, and oxygen are discussed in terms of the height resolution they permit in studies of both constituent and temperature distribution. Radiometer sensitivities are reviewed, and the linear statistical inversion technique of Westwater and Strand

is discussed. It is concluded that the major source of error in carrying out the inversion will result from inaccuracies in the absorption coefficients. Past and current observation programs are reviewed and the prospects for future work are briefly discussed.

1. INTRODUCTION

In 1945 R. H. Dicke, employing a microwave radiometer developed by himself (Dicke, 1946), and his associates at the MIT Radiation Laboratory carried out the pioneer investigation of atmospheric absorption by passive microwave radiometric means (Dicke, et al., 1946). They measured the thermal emission from the atmosphere at 1.00, 1.25, and 1.50 cm wavelengths and compared their results with calculations based on simultaneous radiosonde measurements and the theoretical formulas for oxygen and water vapor absorption developed by Van Vleck (1947a, b). They found the agreement to be satisfactory with some qualifications. Following World War II and with the development of millimeter wave apparatus, atmospheric absorption measurements were carried out with greater precision and to higher frequencies, largely at the University of Texas and at the Bell Telephone Laboratories (Hogg, 1968). In addition, laboratory measurement of absorption by atmospheric constituents, work which was begun during the war, was pursued at a number of laboratories. It was then suggested that the microwave absorption of the atmospheric gases, now better understood, could serve as a tool for remotely probing the structure of the atmosphere (see Barrett, 1963). Barrett and Chung (1962) showed in detail how ground based studies of the emission by the 1.35 cm line of water vapor could provide data on the distribution of water vapor in the atmosphere, particularly at high altitudes. Also, Meeks and Lilley (1963) demonstrated that observations of the emission from the 5-6 mm band of oxygen at various heights in the atmosphere would yield data on the temperature distribution in the atmosphere. It is our purpose in this review to discuss the present state of these ideas and to suggest what some of the future developments may be.

Three different types of ground based observations have been suggested: measurement of the spectrum of absorption of the sun's radiation by an atmospheric constituent, measurement of the emission spectrum of an atmospheric constituent, and measurement at one frequency of the zenith angle dependence of the absorption or emission of the atmosphere. In each case a group of data are obtained which depend on the detailed distributions in the atmosphere of the absorbing constituents and the temperature and pressure. One then hopes to infer some information about these

distributions from the data. In the following we shall review the relevant factors: the absorption coefficients, the formal integral equations, the character of the kernels, the measurement accuracy of microwave radiometers, and the amount of information that one should expect from inverting the integral equations. We will then discuss past and current efforts and what the prospects for the future are.

2. ABSORPTION COEFFICIENTS

Figure 1 shows the run of the atmospheric absorption at the zenith. The curve is based on the best available data on water vapor and oxygen absorption. Rosenblum (1961) has reviewed all the experimental data on absorption by water vapor and oxygen prior to 1961. The water vapor lines at 13.5 mm, 1.63 mm and $\lambda < 1$ mm are evident as are the oxygen band at 5-6 mm and the line at 2.5mm.

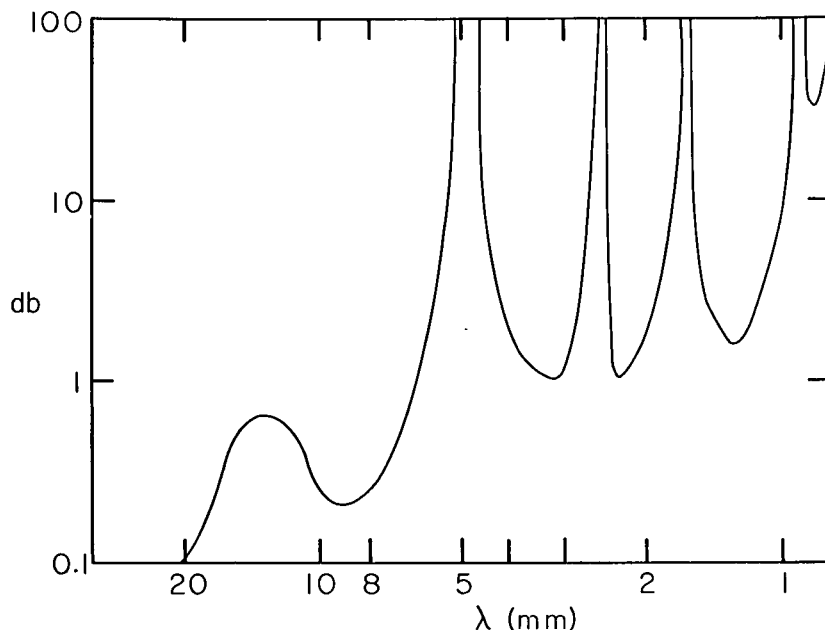


Fig. 1: Absorption of the atmosphere at the zenith due to water vapor and oxygen.

Table 1 lists the atmospheric constituents which absorb microwaves (Glueckauf, 1951). The approximate abundances and the wavelengths at which the constituents absorb are also shown. The right hand column gives an estimate of the peak absorption of a single strong line of each constituent near 1 cm, except for CO which has

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its longest wavelength line at 2.6 mm. With the exception of OH and O₃ the gases lie mostly within the troposphere where the mean line width, determined by pressure broadening, is in the range 800 - 2500 MHz. With this breadth and consequent poor contrast, the minor constituents are difficult to observe against the background of water vapor and oxygen absorption. The expected antenna temperature at the peak of each line may be estimated as follows: For an emission experiment the atmosphere acts like an absorber at about 280 °K and the antenna temperature will be approximately 280 times the peak absorption. If the sun is observed, the absorption dip in degrees will be approximately 5000 times the peak absorption. Observation at large zenith angles will give larger signals. Gases marked with an asterisk are largely industrial effluvia and are hence only transitory. Evidently, few of the trace components will be easily observed by microwave means. In contrast to the other traces, ozone lies in a layer above twenty kilometers where it produces a sharp line of about 200 MHz mean width, and it therefore stands out above the background. OH has a similar distribution but its probable abundance is too low for it to be detected. The final item in the table is water clouds. Liquid water is a good absorber near 1 cm, its absorption spectrum approximately proportional to λ^{-2} . If the clouds consist of small droplets, 0.3 mm or less in size, scattering within the clouds is unimportant and the cloud absorption spectrum will correspond to λ^{-2} (Kerr, 1951). Water clouds are readily detected by a microwave radiometer. On the other hand, cirrus clouds, composed of ice, are practically transparent.

Table 1: Atmospheric constituents that absorb microwaves. The wavelength intervals where the strongest lines lie are shown along with the peak absorption of a line near 1 cm estimated from the tables of Ghosh and Edwards (1956).

Component	Amount (cm-atmos.)	λ (mm)	Peak Absorption
O ₂	167,400	5-6, 2.5	—
H ₂ O	800-22,000	13.5, 1.63, $\lambda < 1$.007-0.18
CO*	0.05-0.8	2.6, 1.3, etc.	.0004-.007
SO ₂ *	0-1.0	4-16, <u>10</u>	\leq .002
N ₂ O	0.4	12, 6, 4	.001
O ₃	0.25	$\lambda < 30$.0007
NO ₂ *	.0004-.02	20, 12	.00001-.00007
NO	trace	—	—
OH	$\sim 10^{-5}$	—	—
water clouds	—	—	—

The formula for absorption by an isolated line of a gas was given by Van Vleck and Weisskopf (1945) as

$$\alpha = C \nu^2 \left\{ \frac{\Delta\nu}{(\nu-\nu_0)^2 + (\Delta\nu)^2} + \frac{\Delta\nu}{(\nu+\nu_0)^2 + (\Delta\nu)^2} \right\} \quad (1)$$

The constant C is proportional to the gas density, the population of the lower state of the transition, the square of the dipole matrix element, and the inverse temperature. It is assumed that the line is broadened by pressure. For moderate pressures ν_0 , the line center frequency, is constant and the line width $\Delta\nu$ is proportional to pressure. A band of lines is given by a superposition of terms of the form (1). Measurements of absorption by atmospheric gases have generally been interpreted in terms of (1) with the data determining the parameters C , $\Delta\nu$, and ν_0 . The temperature dependence of C and $\Delta\nu$ are determined by both experiment and theory (Townes and Schawlow, 1955). At low and moderate pressures the line shape factor (1) fits the data quite well. The formula breaks down at very low pressures where the line broadening is due to the doppler effect. This occurs at pressures corresponding to altitudes of about 80 km or higher in the atmosphere. At pressures such that $\Delta\nu$ is comparable to ν_0 agreement with (1) is obtained only if $\Delta\nu$ is made a non-linear function of frequency and ν_0 is allowed to shift to zero frequency as the pressure is increased. These effects have been studied in the ammonia spectrum by Bleaney and Loubser (1950). At one atmosphere pressure these effects are small but not negligible in the spectra of water vapor and oxygen, the principal microwave absorbers in the earth's atmosphere.

Water vapor has strong absorption lines at 13.5 mm and 1.63 mm and a great many strong lines at wavelengths short of one millimeter. Inspection of (1) shows that when $\nu_0 \gg \nu$, α is proportional to ν^2 . Hence in the neighborhood of the 13.5 line the effect of the higher frequency lines should be representable by a single term proportional to ν^2 . Van Vleck (1947a) calculated the magnitude of this non-resonant term as well as the resonant 13.5 mm line and compared his results with the laboratory data of Becker and Autler (1946). Good agreement was obtained only if the magnitude of the non-resonant term was increased by about four times the calculated value. Subsequent measurements both in the field (Tolbert and Straiton, 1960) and in the laboratory at high pressures (Ho, et al., 1966) confirm this discrepancy. Ho, et al., (1966) also found a substantially different temperature dependence for the non-resonant term than the theoretical dependence. One may conclude that the water vapor absorption is best understood in the neighborhood of the 13.5 mm line. With the above adjustment in the non-resonant term and with temperatures near 300 °K the water vapor absorption formulas as summarized by Barrett and Chung (1962) are probably

correct within about 10% near the 1.35 cm line. More accurate measurements would be desirable particularly over a wider range of frequencies and temperatures.

Oxygen, the other principal atmospheric absorber, has a complex spectrum consisting of a band of lines in the range 5-6 mm, an isolated line at 2.5 mm, and non-resonant absorption ($\nu_0 = 0$) which dominates at wavelengths longer than 3 cm. Measurements of the line frequencies and widths have been made in the laboratory at low pressures and pressures up to 1 atmosphere (Artman and Gordon, 1954, Anderson, *et al.*, 1952). Direct measurements of atmospheric absorption by oxygen have also been made (see Hogg, 1968). The measurements have been reviewed by Meeks and Lilley (1963) and more recently by Westwater and Strand (1967a). It was found that nitrogen is about 75% as effective as oxygen in broadening the oxygen absorption. In addition, whereas the line width was found to be about 1.95 MHz/mmHg at low pressure for all the lines, about half that value must be used in the Van Vleck-Weisskopf sum to predict the absorption at one atmosphere pressure. How the transition must be made is not yet understood, although Meeks and Lilley make the reasonable suggestion that the transition be assumed linear with height in the atmosphere between pressures of 19 mmHg and 207 mmHg. Even at one pressure and temperature the Van Vleck-Weisskopf sum with a single half-width parameter does not exactly fit the measurements. Figure 2 is taken from the atmospheric absorption studies of Crawford and Hogg (1956). The fit for a line width parameter of 600 MHz is good but not perfect. In view of this discrepancy and the uncertainty in the variation of the half width parameter with pressure, we may suppose that the accuracy with which the oxygen absorption coefficients may be predicted is not better than 5%. We shall see that this accuracy is not quite adequate for temperature sounding experiments.

In addition to further experimental studies to improve the precision of the absorption coefficients, theoretical work on the line shape function may be useful, particularly for the oxygen band and the infrared water vapor band. Recently, Ben Reuven (1965, 1966) has proposed a new line shape function and shown how it describes the absorption spectrum of ammonia much more adequately than the Van Vleck-Weisskopf formula, especially at high pressure. Even at low pressures Ben Reuven's formula predicts an absorption coefficient in the wings of the ammonia band that agrees better with measurement (see also Townes and Schawlow, 1955). The application of Ben Reuven's work to the oxygen band and to the sum of infrared water vapor lines, if possible, should prove fruitful.

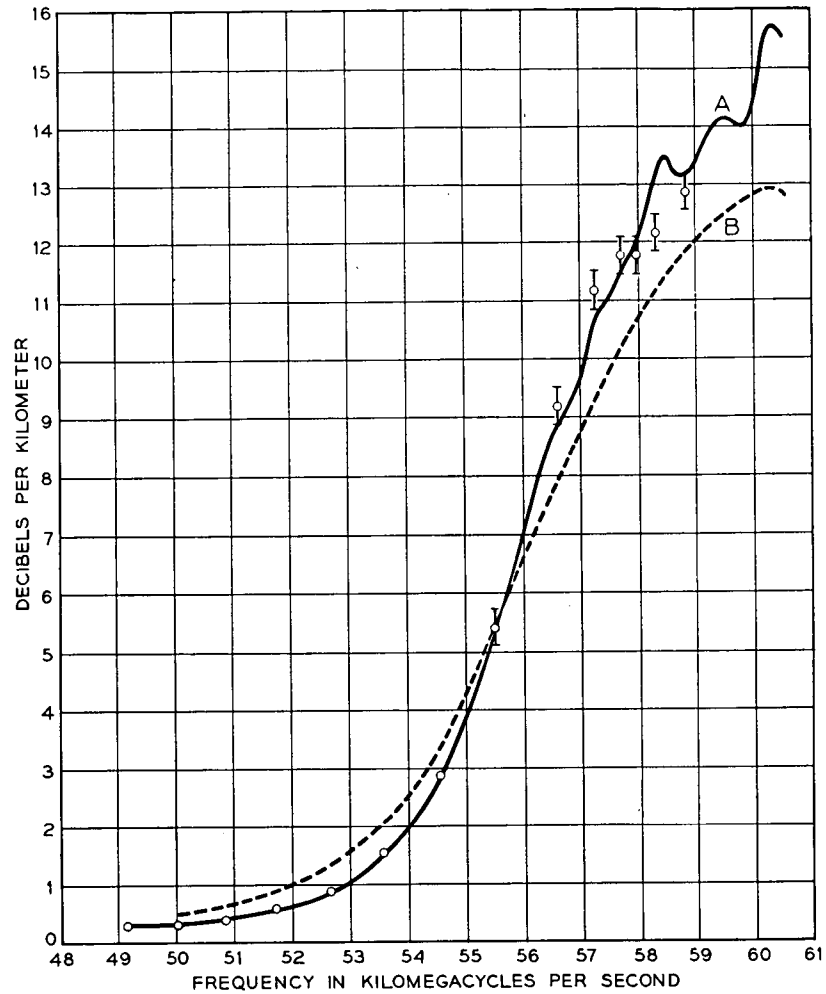


Fig. 2: Calculated and measured absorption by air at sea level. The dots represent the experimental data; the vertical lines indicate the spread in the measured values. Curves A and B are calculated curves of oxygen absorption using line breadth constants of 600 and 1200 MHz respectively. (After Crawford and Hogg, 1956).

3. THE INTEGRAL EQUATIONS

There are basically three different types of radiometric observations that may be made from the ground: a) One directs his antenna at the sun (or moon) and measures the spectrum of atmospheric absorption in the neighborhood of an absorption line or band. b) The antenna is oriented in a fixed direction away from the sun and the spectrum of the atmospheric emission is measured. c) The variation of the atmospheric emission is measured at one frequency as a function of the zenith angle of the antenna. In each case there results a group of data each datum of which results from a somewhat independent integration over the absorption coefficient of the atmospheric constituent and the temperature and pressure distributions in the atmosphere. Our program is then to invert this integral equation to obtain either the atmospheric temperature profile or the distribution of the absorbing constituent. The form of these equations follows from the theory of radiative transfer in the atmosphere.

The distribution of radiant intensity in the atmosphere is governed by the equation of radiative transfer (Chandrasekhar, 1960). With the assumption of local thermodynamic equilibrium and that scattering of microwaves in the atmosphere is negligible, the distribution of intensity, I_ν , in the atmosphere obeys the simple equation

$$\frac{dI_\nu}{ds} + \alpha I_\nu = \alpha B_\nu(T) \quad (2)$$

where α is the absorption coefficient and $B_\nu(T)$ is the Planck function. In the microwave region of the spectrum B_ν is directly proportional to T for all temperatures of physical interest.

$$B_\nu(T) \cong \frac{2kT\nu^2}{c^2} \quad (3)$$

where k is Boltzmann's constant. The equation takes on a simple form if we replace I_ν by a brightness temperature T_B defined so that

$$I_\nu \equiv \frac{2kT_B}{\lambda^2} \quad (4)$$

We will assume the atmosphere to be horizontally homogeneous and essentially planar, having properties that are only a function of

the distance h above the surface of the earth. This model serves quite well for observations from the zenith to within about 7° of the horizon. The solution of (2) for the brightness temperature T_B of a pencil of radiation incident on the ground at a zenith angle z and azimuth angle ϕ is

$$T_B(\nu, z, \phi) = T_E(\nu, z, \phi) e^{-\tau_0 \sec z} + \int_0^{\tau_0 \sec z} T(\tau) e^{-\tau \sec z} d(\tau \sec z) \quad (5)$$

where $d\tau = \alpha(\nu, h)dh$,

$$\tau(h, \nu) = \int_0^h \alpha(\nu, h') dh' \quad \text{and} \quad \tau_0(\nu) = \int_0^H \alpha(\nu, h) dh . \quad (6)$$

H is the extent of the atmosphere, T_E is the brightness of sources outside the atmosphere (such as the sun), and $T(\tau)$ is the temperature of the atmosphere as a function of optical depth. If $G(z, \phi; z', \phi')$ is the gain function of the antenna, the antenna temperature with the axis in the direction (z', ϕ') is

$$T_A(\nu, z', \phi') = \frac{1}{4\pi} \int T_B(\nu, \phi, z) G(z, \phi; z', \phi') d\Omega \quad (7)$$

The three cases discussed above may now be considered separately. When the antenna is pointed toward the sun, the first term in (5) dominates because the brightness of the sun is much greater than that of the atmosphere.

$$T_A(\nu, z', \phi') \cong \frac{1}{4\pi} \int T_{ES} e^{-\tau_0 \sec z} G(z, \phi; z', \phi') d\Omega \quad (8)$$

If the entire main beam of the antenna lies within the solid angle of the sun, (8) becomes

$$T_A(\nu, z', \phi') = \eta_B T_{ES} e^{-\tau_0 \sec z'} \quad (9)$$

where η_B is the main beam efficiency (Kraus, 1966). Then

$$\tau_0(\nu) = - \frac{\partial [\ln(T_A(z', \nu))]}{\partial (\sec z)} \quad (10)$$

In general, $\alpha(\nu, h)$ is nearly a linear function of the density of the absorbing gas, so that (6) and (10) may be combined to yield the following linear integral equation for the density $\rho(h)$ (Staelin, 1966).

$$\int_0^h \rho(h) \left[\frac{\alpha(\nu, h)}{\rho(h)} \right] dh = - \frac{\partial \{ \ln [T_A(z', \nu)] \}}{\partial (\sec z)} \quad (11)$$

If the pressure and temperature distributions with height are assumed, $\alpha(\nu, h) / \rho(h)$ is a known function and (11) may be solved for $\rho(h)$ (see Staelin, 1966, for a generalization of (11) to a non-planar atmosphere).

For case (b) the antenna is directed away from the sun, often toward the zenith, and T_E is just the weak isotropic cosmic background, approximately 2.7 °K (see e.g. Wilkinson, 1967). Because some of the sidelobes of the antenna pattern are directed at the ground, a term $e(z, \phi) T_G$ should be added to (5) in (7). T_G is the ground temperature and $e(z, \phi)$ is the ground emissivity. (7) then becomes

$$\begin{aligned} T_A(z', \nu) - \frac{1}{4\pi} \int \left[2.7 e^{-\tau_0 \sec z} + e(z, \phi) T_G \right] G(z, \phi; z', \phi') d\Omega \\ \tau_0(\nu) \sec z \\ = \frac{1}{4\pi} \int \left\{ \int_0^{\tau_0 \sec z} T(\tau) e^{-\tau(\nu)} \sec z d(\tau \sec z) \right\} G(z, \phi; z', \phi') d\Omega \end{aligned} \quad (12)$$

If G is a sharp function compared to the angular dependence of the term in the curly brackets, the right hand side of (12) may be approximated by

$$K(z') \int_0^{\tau_0 \sec z'} T(\tau) e^{-\tau \sec z'} d(\tau \sec z') \quad (13)$$

$K(z')$ is a correction for the finite antenna beamwidth and probably can be worked out with sufficient accuracy with a standard model atmospheric distribution of T and τ . If $\tau(h)$ is assumed, (12) is an integral equation for $T(h)$. It will, in general, be slightly non-linear because τ is somewhat a function of temperature. If $\tau_0 \ll 1$, as it will be for ozone, the exponential term in (13) is approximately unity, and (13) may be written

$$K(z') \sec z' \int_0^H \rho(h) \left[\frac{T(h) \alpha(\nu, h)}{\rho(h)} \right] dh \quad (14)$$

Equation (12) is then essentially like equation (11). One important difference is that T_A on the left side of (12) must be measured absolutely whereas the zero point in the scale of T_A on the right side of (11) is unimportant.

For case (c), in which the antenna temperature as a function of zenith angle is measured at just one frequency, equation (12) applies. In order to attain sufficiently large values of $\sec z'$, the antenna must be able to look to within about one degree of the horizon. This requires an antenna with a complex sidelobe pattern. In this case the ground contribution term on the left hand side of (12) becomes both large and also difficult to evaluate.

Equations (11) and (12) are Fredholm integral equations of the first kind and may be written

$$T(x) = \int_a^b \rho(y) K(x, y) dy \quad (15)$$

where the kernel function $K(x, y)$ is often called the weighting function. Before discussing the possible solutions to (15), it will be instructive to examine the weighting functions that occur in practice.

4. CHARACTER OF THE WEIGHTING FUNCTIONS

An inspection of the kernel functions that occur in practice reveals how much information one can hope to recover from an actual inversion of the integral equation discussed above. A measurement of the spectrum of the absorption of solar radiation by a single line of ozone provides an example of an integral equation of type (a) discussed above. Furthermore, because the total abundance of telluric ozone is slight and hence $\tau_o(\nu) \ll 1$, a similar equation (see (14) above) is obtained for an emission measurement. The normalized ozone weighting functions for different frequencies in the neighborhood of the 37.8 GHz ozone line are shown in figure 3 (see Caton, et al., 1967). The functions are peaked with half widths of about 15 kms, suggesting that the mean ozone distribution at the right of the figure may be sliced into about 4 layers of about 10 kms thickness each with each layer contributing approximately independently to the integral in (11). Because of the width of the weighting functions, further resolution of the distribution in

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height is probably not possible. The weighting functions for Umkehr observations of ozone have the same width as these (Mateer, 1965). Hence, the spatial resolution of the microwave measurements and the Umkehr measurements is the same. Mateer (1965) finds,

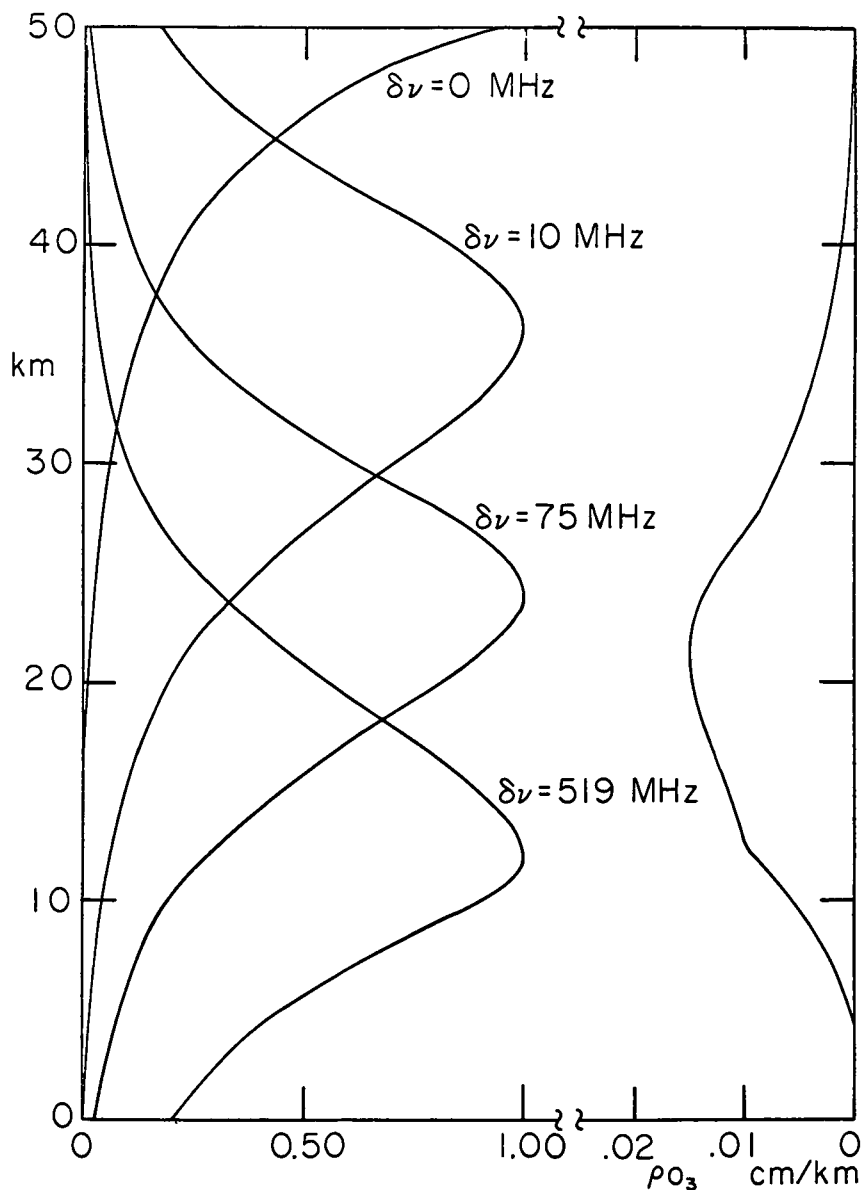


Fig. 3: The curves on the left are ozone weighting functions. The one on the right is a mean ozone distribution.

in fact, from a detailed investigation of the kernel for the Umkehr integral equation that at most four independent pieces of information about the ozone distribution may be obtained from an Umkehr measurement. The microwave weighting functions for water vapor have about the same width as those of ozone (Staelin, 1966). However, the water vapor is largely confined to a layer extending only up to about 8 km above the ground, and therefore only 2 or 3 independent data concerning the water vapor distribution may be obtained from a ground based microwave observation.

A study of the spectrum of emission at the zenith from the long wavelength wing of the 5-6 mm oxygen band provides an example of case (b) above. The unknown function in this case is the temperature distribution in the atmosphere, see (12). Figure 4 shows the normalized weighting functions at various frequencies next to a radiosonde temperature measurement taken at Oakland, California, December 10, 1967. It is clear that the best resolution is obtained near the ground and that only about 3 independent data concerning the temperature distribution may be obtained from the ground based observation. Because the resolution is best near the ground, one would hope to detect interesting distributions such as the temperature inversion which is evident in the figure.

An example of the kernel that one obtains using antenna elevation angle ϵ rather than frequency as the measurement variable is shown in Figure 5 (Staelin, 1966). The effect of curvature of the earth is accounted for in the figure but not atmospheric refraction. Resolution comparable to that shown in Figure 4 is possible but requires that the antenna be tipped to within a degree of the horizon.

Normalization of the weighting functions in Figure 3 demonstrates the resolution in the observations but hides an important fact, namely, that the higher weighting functions are stronger. In fact, the function for the center of the line (the absorption coefficient for the center of the line) is proportional to $(\Delta\nu)^{-1}$ and hence to p^{-1} and therefore increases approximately exponentially with height up to about 80 km above which $\Delta\nu$ is determined by doppler broadening. As a result, absorption near the center of the line which takes place largely at the higher altitudes is intense even though the gas density may be low at those altitudes. Because microwave measurements permit very high resolution, it is possible to measure the intensity in the line core and hence to study the gas or temperature distribution at high altitudes.

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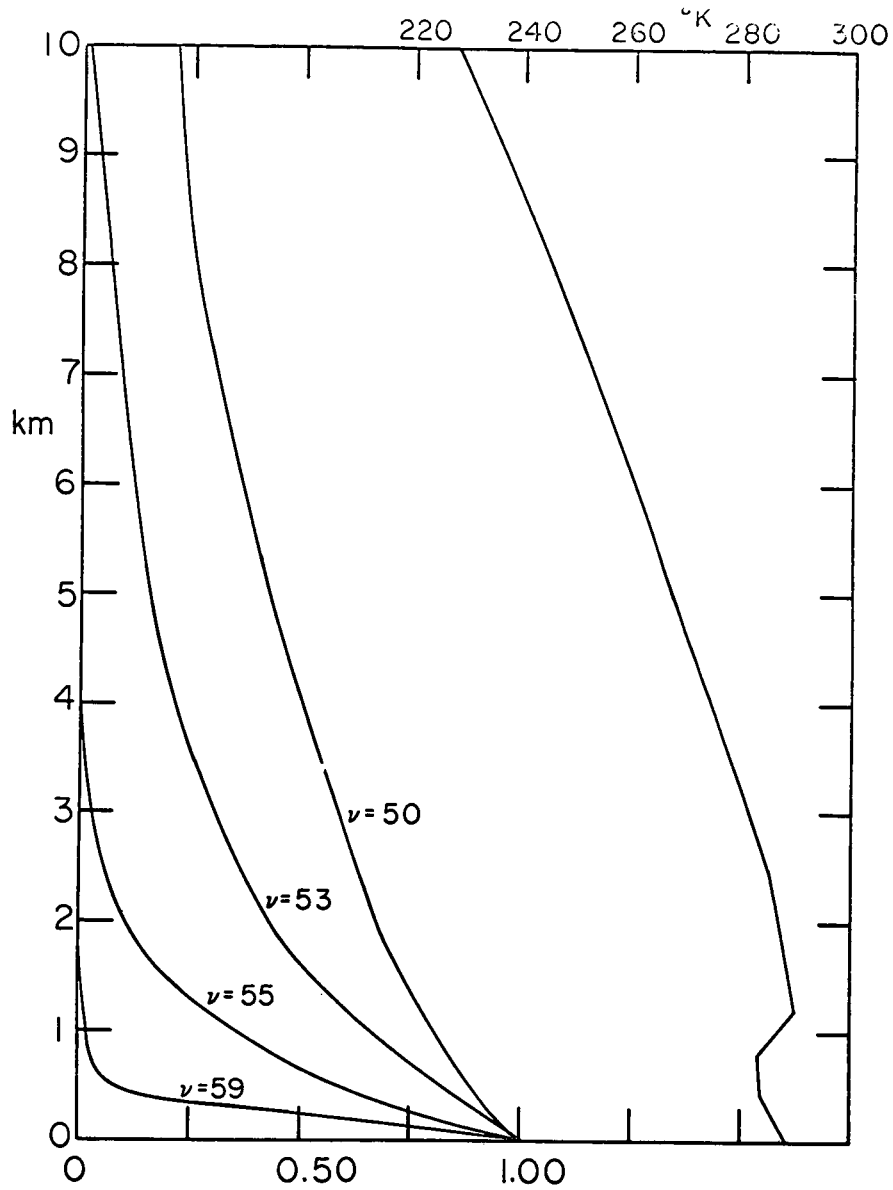


Fig. 4: Weighting functions for O_2 are on the left for different frequencies (in GHz). The right hand curve is the radiosonde temperature profile at Oakland, California, Dec. 10, 1967.

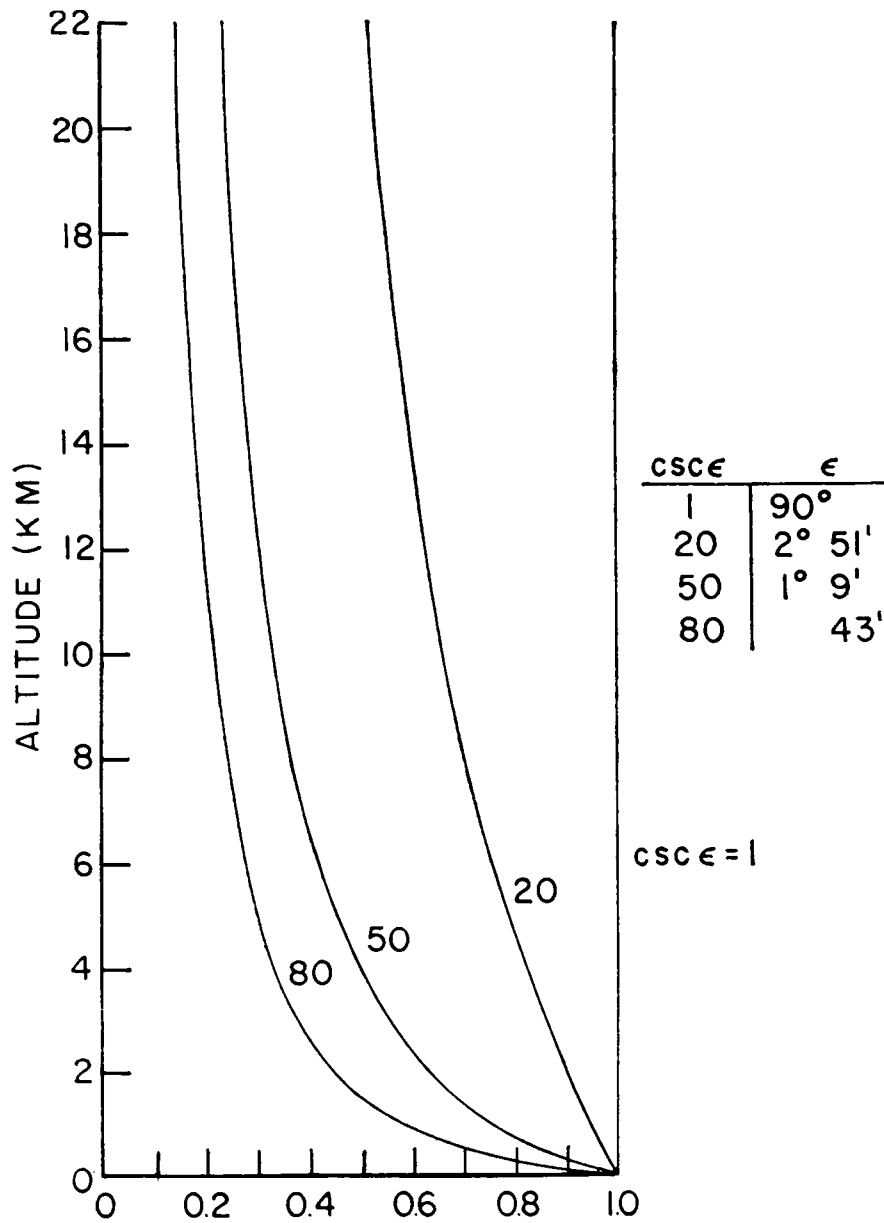


Fig. 5: Weighting functions for antenna tipping (after Staelin, 1966).

5. RADIOMETER SENSITIVITIES

Before discussing the details of the inversion further, let us consider the accuracy with which the radiation measurements can be made. The accuracy will have, of course, a strong bearing on the quality of the inference that can be drawn from the measurements. There are two types of uncertainty in radiometry: a) absolute calibration error, and b) error due to finite signal to noise ratio.

The signal to noise ratio of a radiometer is proportional to the system noise temperature and inversely proportional to the square root of the product of predetection bandwidth and integration time (Krauss, 1966). If absorption against the sun is being studied, the system temperature must include the solar brightness temperature, about 6000 °K or more. For an emission experiment, only the receiver noise temperature matters very much. For a crystal mixer it is not likely to be much less than 2000 °K in the millimeter range. On the other hand, parametric amplifiers or masers with noise temperatures of about 100 °K now appear to be possible in this wavelength range. Table 2 contains the expected radiometer output fluctuation for the above three system temperatures for an hour's integration time and for several typical bandwidths. The narrowest bandwidth is required for measuring a sharp line core as discussed in Section 4. As Table 1 shows, the ozone absorption is weak, having a peak emission temperature at the zenith of only 0.2 °K. Nevertheless, an inspection of Table 2 shows that measurement with a multichannel spectrometer and a low noise amplifier will

Table 2: Radiometer output fluctuation for various system temperatures and bandwidths and for 1 hour observation time.

System Temperature (°K)	Bandwidth (MHz)	ΔT (°K)
8000	2	.08
	10	.04
	100	.012
100	2	.001
	10	.0005
	100	.00016
2000	2	.02
	10	.01
	100	.003

permit observing an ozone emission profile with an accuracy of a few percent. Observation of the emission from atmospheric oxygen and water vapor can be made with better than 1 degree accuracy even with a 2000 °K system temperature.

The other source of radiometric uncertainty is absolute calibration error. For a narrow line like that of ozone, the continuum away from the line provides a reference. For wide lines or bands calibration must be made with respect to absolute black body terminations. These comparisons are difficult. Nevertheless, the recent experience of a number of workers in measuring the cosmic background radiation (see, for example, Wilkinson, 1967) has shown that absolute calibration accuracies of 0.5 °K or better are possible.

6. INFORMATION CONTAINED IN THE INTEGRAL EQUATIONS

If a single line is observed, such as that of ozone or of water vapor, the area under the profile depends only on the total amount of the absorber present and not on its distribution or on the pressure distribution. (There is a weak dependence on the temperature distribution along the path.) Hence the total abundance of the gas may be measured with an accuracy which is simply proportional to the radiometer accuracy and the certainty in the line strength. Such a determination will be simple for a narrow ozone line but much more difficult for the very broad water vapor profile which results from water vapor near the ground. It has been pointed out by Barrett and Chung (1962) that because water vapor appears to have a constant mixing ratio in the stratosphere this high altitude vapor should produce a narrow intense line superposed on the broad line associated with vapor in the troposphere. The total stratospheric abundance associated with such a narrow line should be readily determinable.

Working out the distribution of a constituent with height requires actual inversion of the integral equation, and in this case the effect of noise on the inferred distribution is somewhat obscure. In general, measurements will be made at a discrete set of frequencies or antenna elevation angles. Hence, in practice one replaces the integral equation (15) by an equivalent set of algebraic equations. Suppose, for example, one wished to infer the tropospheric vertical temperature structure from measurements of the spectrum of antenna temperatures at the zenith in the wing of the 5-6 mm oxygen band. The integral equation is of the form (12)

$$T_e(\nu) = \int T(h) K(h, \nu) dh \quad (16)$$

T_e includes the ground and background radiation. The integral may be replaced by a sum either by dividing the atmosphere into slabs or by writing $T(h)$ as a sum of known (possibly orthogonal) functions with unknown coefficients. In the former case one gets

$$T_{e_i} = \sum T_j K_{ij} \quad \text{or} \quad (T_e) = (K)(T) \quad (17)$$

It is well known that an attempt to invert (17) directly to obtain (T) will meet with disaster for two reasons. In the first place it should be clear from the form of the kernel functions that the data are somewhat coupled so that the matrix (K) is nearly singular. One finds, in fact, that if one does a model calculation, the round off error in even a large digital computer will produce errors of a few percent in the derived temperature distribution. The other source of difficulty is the uncertainty in the measurement of T_e and the inaccuracy in the absorption coefficients which go into (K) . The presence of noise in (17) makes the solution non-unique and aggravates the instability problem. Evidently, no useful solution may be extracted from the class of possible solutions without the a priori application of some constraint. The first work on this problem is that of Phillips (1962) who showed that a stable solution could be obtained if the solution is constrained to have a minimum second derivative. Twomey (1963) discussed other possible constraints including the least squares fit of the solution to some trial function. These ideas have been further developed by Twomey (1965), Twomey and Howell (1963), Mateer (1965), Wark and Fleming (1966), and most recently by Westwater and Strand (1967a, b).

Westwater and Strand argue that the inversion should be viewed as the improvement (by the radiation measurements) of the statistics of the temperature distribution. For example, daily measurements of the air temperature profile at many stations have been made with radiosondes for more than two decades. Thus for every station there is a yearly, seasonal, or monthly mean profile and a standard deviation of the temperature at each level in the atmosphere. Furthermore, because the profiles are continuous functions, there is significant correlation between the temperatures at nearby levels. The observations of the emission from the oxygen band are then to be used to find a solution to (17) such that the derived temperature distribution is a least squares fit to the temperature profile. The minimization is with respect to the joint probability distribution of the temperature profile and the observational error. The two or three independent pieces of data in the measurement are distributed over the profile reducing the variance where the weighting functions are the most sensitive. If T_0 is the mean profile and S_T and S_e are the covariance matrices of the profile and the experimental data respectively, then the optimum linear estimate of (T) is given by Westwater and Strand, 1967a)

$$(T) = (T_o) + (X)^{-1}(K)^*(S_e)^{-1}[(T_e) - (T_{e0})] \quad , \quad (18)$$

$$\text{where} \quad (X) = (S_T)^{-1} + (K)^*(S_e)^{-1}(K) \quad (19)$$

The covariance matrix of $(T - T_o)$ is given by $(X)^{-1}$. The diagonal elements of the latter are the mean-square variances at the different heights. Figures 6 and 7 are example model calculations by Westwater and Strand (1967b) appropriate to the oxygen sounding problem. The curves show the variance with height for profiles derived from sets of measurements at 5 frequencies with different assumed measurement errors, σ_e . The σ_e are absolute uncertainties in the antenna temperatures and are taken to be the same at each frequency. The curve for $\sigma_e = \infty$ shows the a priori profile statistics. Figure 7 shows the results that are obtained if the ground temperature can be constrained by an independent measurement (perhaps with a thermometer).

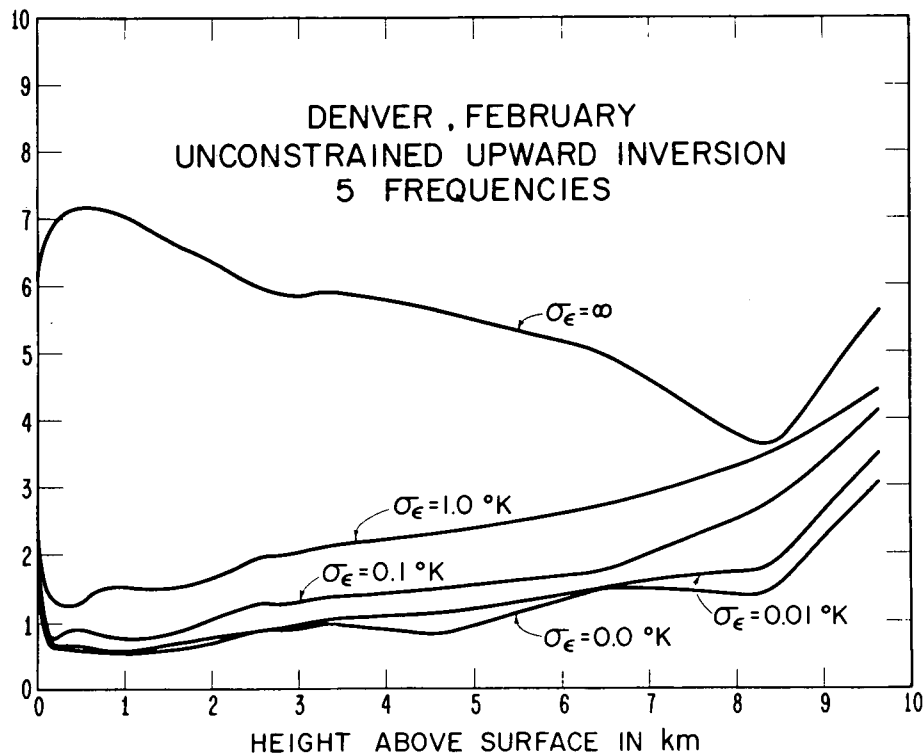


Fig. 6: Accuracies of several simulated upward inversions for temperature profiles for different levels of measurement error, $\sigma_e = \infty$ shows the a priori profile statistics. The ordinate is °K. (Westwater and Strand, 1967).

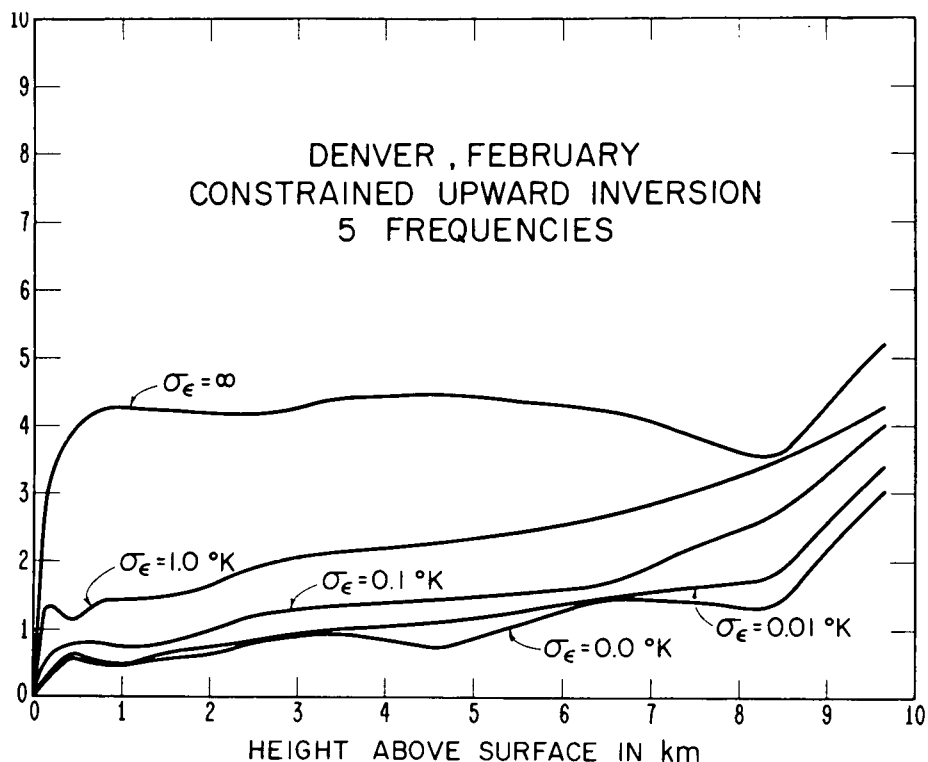


Fig. 7: Accuracies for several simulated upward inversions for temperature profile for different levels of measurement error, σ_{ϵ} , with the surface temperature constrained. The ordinate is $^{\circ}\text{K}$. (Westwater and Strand, 1967).

It is clear from the figures that significant results may be obtained with measurement errors as large as 1.0°K . One may well ask whether measurement errors as small as 1.0°K are presently possible. In section 5 we concluded that an absolute accuracy of 1.0°K was well within the capabilities of current radiometers. A more serious problem, particularly for the temperature sounding studies, is the inaccuracy in our knowledge of the absorption coefficients. For example, at 50 GHz the atmospheric optical depth is about 0.3 and hence the sky brightness temperature at the zenith is about 100°K . If this opacity, which is mostly due to oxygen, is uncertain by 5%, an intolerably large error of 5°K results. This error has the same effect as a measurement error.

7. PAST AND CURRENT PROGRAMS

To date, the observational possibilities in ground based passive microwave probing of the atmosphere have been only marginally exploited. Quite often the sky brightness is measured primarily so that the inferred atmospheric absorption can be used to correct astronomical observations (see, e.g. Shimabukuro, 1966; Tolbert, et al., 1965).

Wulfsberg (1964) measured sky brightness temperatures throughout a year at 15, 17, and 35 GHz. Falcone (1966) compared these data with theoretical temperatures based on concomitant radiosonde data and found that the correlation was best if an oxygen half-width parameter of 750 MHz at NTP was used. No attempt to invert this data has been published.

Staelin (1966) has published solar absorption spectra in the neighborhood of the 1.35 cm water vapor line for both clear and cloudy days. He shows how the abundance of the liquid water clouds, because of their characteristic λ^{-2} spectra, can be readily determined. For clear days he found that the difference between measured spectra and theoretical spectra from radiosonde data varied between 0 and 15%. The spectra are shown in Figure 8. As discussed in section 6 above, Barrett and Chung (1962) suggested that high altitude water vapor might be detectable as a narrow intense emission feature at 1.35 cm. Figure 9 shows some model distributions and corresponding spectra as calculated by Croom (1965). Bonvini, et al., (1966) reported measurements at Slough in which they did not detect the line and placed an upper limit of about 2 °K on the effect. Recently, Staelin (1968) has reported detecting a weak line at a lower level than 2 °K. The observed signal is in agreement with a constant stratospheric mixing ratio of about 2×10^{-6} as observed by balloon (Mastenbrook, 1968).

Both emission and absorption of ozone has been detected recently at Berkeley (Caton, et al., 1967), at the Ewen-Knight Corporation (Caton et al., 1968), and at MIT (Barrett, et al., 1967). The very strong 101.7 GHz line of ozone as seen against the sun by the Ewen-Knight group is shown in Figure 10. In each case only an approximate estimate of the total ozone abundance was obtained and no attempt at inversion was made. As in the case of stratospheric water vapor, the very high altitude ozone should produce a sharp central core. Hunt (1966) has estimated that the ozone abundance above 53 km should be enhanced at night, and Carver, et al., (1966) have reported detecting an enhancement with a rocket-borne UV spectrometer. A careful observation of the core of the microwave line may reveal these diurnal variations.

The current ground-based programs of which the author is aware are as follows: Multichannel studies of ozone and water vapor at MIT; Antenna tipping experiments at 4 mm at the University of Texas

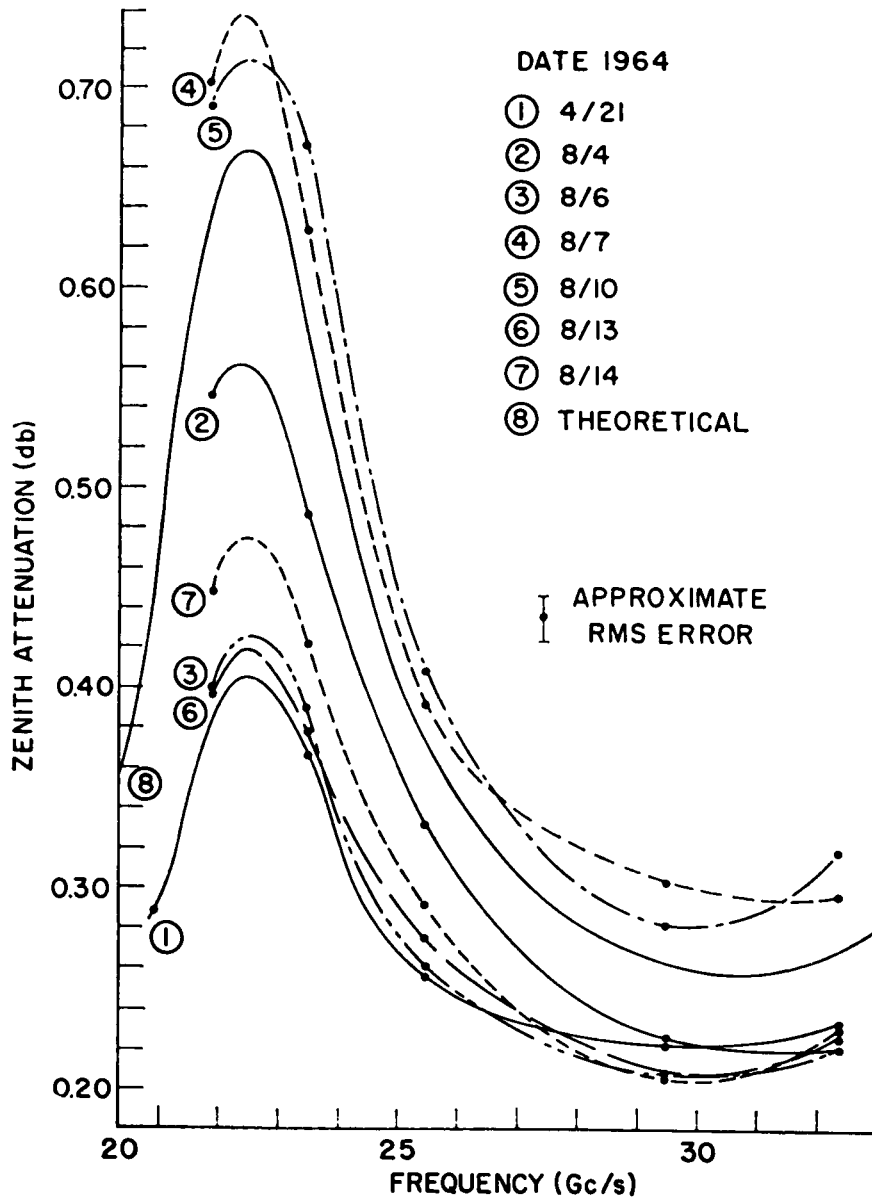


Fig. 8: Measured atmospheric absorption spectra (Staelin, 1966).

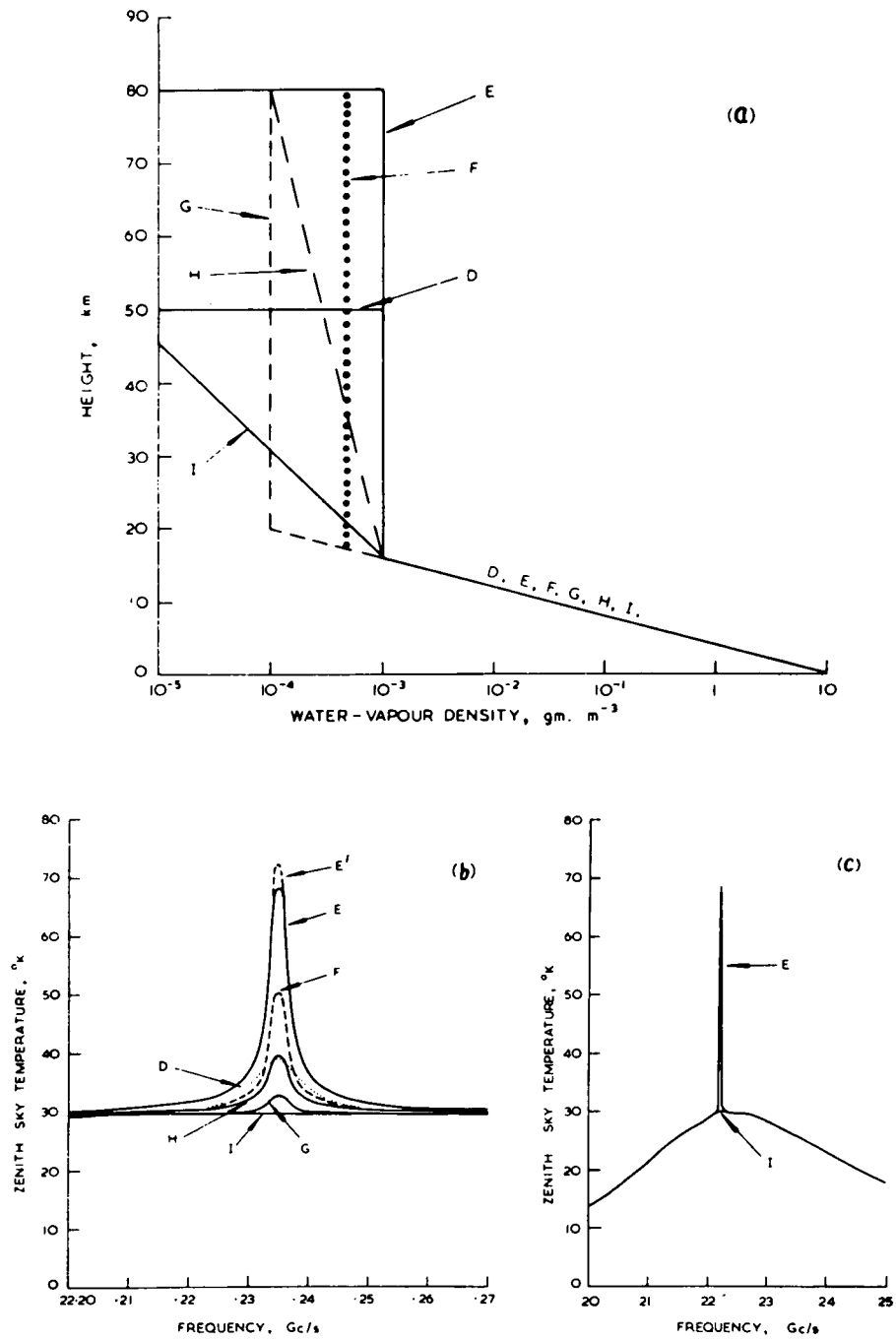


Fig. 9: Zenith sky emission spectra for six hypothetical water-vapor profiles. (a) Water-vapor profiles, (b) corresponding spectra on a fine frequency scale, (c) spectra E and I on a coarse frequency scale. (After Croom, 1965).

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to obtain the tropospheric temperature profile; Both multi-frequency and antenna tipping experiments in Hawaii by the ESSA Boulder Laboratories; At UC Berkeley, multifrequency measurements in the oxygen band for the temperature profile, and multifrequency ozone line measurements.

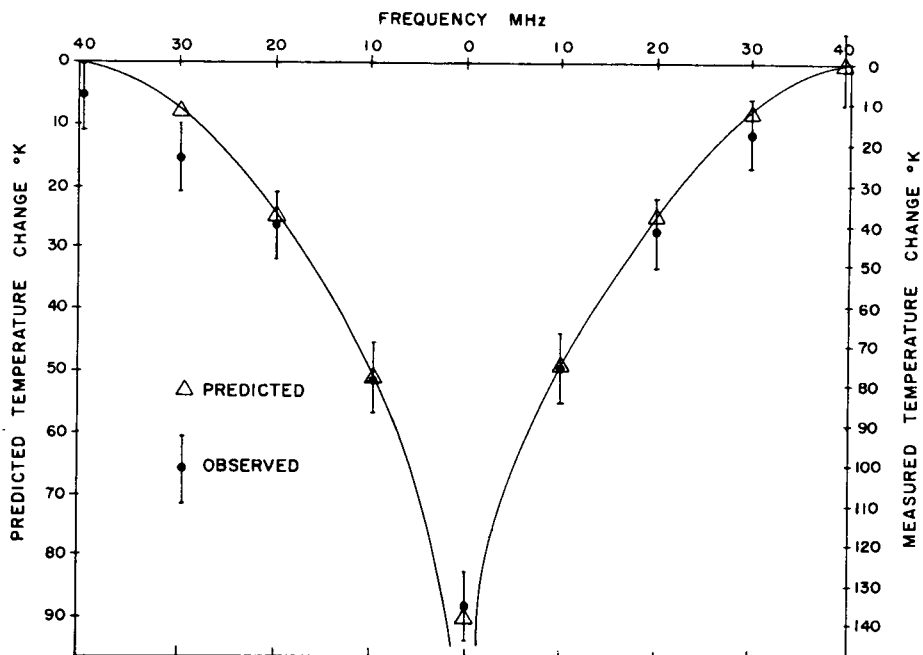


Fig. 10: Measured and predicted ozone profile for the 101.7 GHz ozone line. (After Caton, et al., 1968).

8. METEOROLOGICAL RELEVANCE

Ozone plays an important role in the heat balance of the atmosphere because of its absorption of ultra-violet radiation from the sun and infra-red radiation from the earth. Like Umkehr measurements, the microwave studies of the ozone from the ground will never provide the quality of spatial resolution afforded by balloon sampling. Only gross distribution features can be determined. Unlike the Umkehr observations which must be made at sunrise and sunset, the microwave emission studies can be made at any time of day or night. Hence they can be used for studies of hourly variations and, in particular, the night time high altitude enhancement. The total ozone content varies considerably during the year, especially at middle latitudes and it should be accurately measurable by microwave probing.

The influence of the different kinds of water clouds on the weather is familiar to everyone. There is probably no better way to remotely measure the amount of water in a cloud than with a microwave radiometer. The variable water vapor content can also, in principle, be measured quickly and accurately with a proper microwave radiometer. Furthermore, this vapor measurement can be made even in the presence of water clouds. In contrast, sounding in the infra-red fails in the presence of clouds because they are too opaque.

It is clear from the discussion of Sections 5 and 6 that measuring the emission from the oxygen band permits one to probe the temperature structure of just the first few kilometers. However, this is an important region because it is at these levels that the low lying temperature inversions form. The presence of such inversions is particularly important in urban areas because of the trapping of smog layers by inversions. Although radiosonde measurements naturally provide better resolution, the microwave probing technique offers some advantages: the measurements are more local and, in principle, may be done more quickly and more often.

9. SUMMARY

The prospects for making significant meteorological measurements by passive microwave probing seem to be very good. The measurement precision of radiometers that are currently available (or will soon be available) is adequate. On the other hand, the uncertainties in the gas absorption coefficients are presently too large. It may be that the microwave probing programs that are currently in progress will provide the data which can be used to improve the absorption coefficients. A better procedure is probably to make accurate absorption measurements in the laboratory. Further work such as that begun by Ho, et al., (1966) should be carried out; that is, accurate measurements of the temperature and pressure dependences of absorption in mixtures of gases should be made, and this program should be coupled with theoretical studies of the shape of microwave bands. Both the oxygen band and far infrared water vapor band are not sufficiently understood.

The theoretical machinery for inverting the radiometric data seems now to be well worked out. The observations for which the microwave probing techniques are especially well suited are: determination of total water vapor and ozone content, even in the presence of clouds, and determination of the water content of clouds.

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