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Passive Remote Sensing at Microwave Wavelengths

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Abstract—Passive remote sensing at microwave frequencies has applications which range from meteorology to oceanography and geology. The meteorological applications are the most fully developed and include measurements of the temperature profile of the atmosphere and of the atmospheric distribution of H_2O and O_3. Such measurements can be made from space or from the ground by utilizing the microwave resonances of O_2, H_2O, and O_3 which occur near 1-cm wavelength. Although infrared observations permit similar meteorological measurements, such optical devices are much more sensitive to aerosols and clouds. The small but finite nonresonant attenuation of most moderate clouds at microwave frequencies also permits their liquid water content to be estimated.

At wavelengths longer than 2 cm the microwave properties of the terrestrial surface dominate observations from space, and measurements as a function of polarization and viewing angle yield information about surface temperature and emissivity. Such measurements of the ocean should also permit the sea state to be inferred.

The review has two major parts. The first part reviews the physics of the interactions, the mathematics of data interpretation, and the instrumentation currently available. The second part is applications-oriented and emphasizes the types, accuracy, and relevance of possible meteorological measurements.

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I. INTRODUCTION

PERHAPS the earliest passive microwave observations of the atmosphere were made in 1945 by Dicke [1], [2] and his associates at the M.I.T. Radiation Laboratory. Their observations at 1.00-, 1.25-, and 1.50-cm wavelengths were generally consistent with the results expected on the basis of radiosonde measurements and the theoretical expressions of Van Vleck [3], [4]. Since that time many workers have measured atmospheric properties using wavelengths ranging from millimeters to meters.

In this paper ways in which the wavelength interval 0.1 to 100 cm can be utilized for passive ground-based or space-based meteorological measurements are reviewed. Each region of the electromagnetic spectrum has unique properties which can be exploited for purposes of remote sensing, and in the microwave region these properties include an ability to penetrate clouds and to interact strongly with O_2, H_2O, and other atmospheric constituents. The interactions considered here are those of O_2, H_2O, O_3, clouds, precipitation, sea state, surface temperature, and surface emissivity. Barrett [5] has listed many other constituents which also interact, such as OH, CO, N_2O, and SO_2, but these are presently difficult to observe and are not considered in this review.

The review has two major parts. The first part reviews the

physics of the interactions, the mathematics of data interpretation, and the state-of-the-art in instrumentation. The second part is applications-oriented and reviews the types, accuracy, and relevance of possible meteorological measurements. It also contains several suggestions for further work.

II. TECHNICAL REVIEW

A. Physics of the Interactions

The topics on this section include 1) the relevant equations of radiative transfer, 2) the absorption coefficient expressions for O_2, H_2O, O_3, clouds, and precipitation, and 3) the microwave properties of the terrestrial surface. Both the theoretical expressions and the corresponding experimental verifications are described and referenced. In general, only a fraction of all possible references are given.

1) *The Equations of Radiative Transfer:* At wavelengths longer than 1 mm the Planck function can be simplified because $hv \ll kT$ for all situations of meteorological interest. The symbols h, v, k, T are Planck's constant, frequency, Boltzmann's constant, and absolute temperature, respectively. In this paper rationalized MKS units are used unless stated otherwise. As a result of this low-frequency approximation the power P (watts) received by a microwave radiometer immersed in a blackbody enclosure at temperature T equals kTB, where B is the bandwidth (Hz). Since temperature has direct physical significance, most radiometers are calibrated in terms of antenna temperature $T_A(°K)$, which is the temperature a blackbody at the antenna terminals must have to produce a signal of the observed power P. That is,

$$T_A = P/kB. \quad (1)$$

The measured antenna temperature T_A is in turn related to the angular distribution of power incident upon the antenna. The appropriately polarized power incident upon the antenna from any given direction can be described by an equivalent brightness temperature $T_B(v, \theta, \phi)$ (°K). The antenna temperature is then an average of the brightness temperature weighted over 4π steradians according to the antenna gain function $G(v, \theta, \phi)$. That is,

$$T_A(v) = \frac{1}{4\pi} \int_{4\pi} T_B(v, \theta, \phi) G(v, \theta, \phi) d\Omega. \quad (2)$$

The gain of any particular antenna can be calibrated on an appropriate test range.

The equation of radiative transfer can be used to relate the brightness temperature T_B to the atmospheric composition and temperature $T(z)$ along the line of sight, and to the brightness temperature $T_0(\theta, \phi)$ of the medium beyond the atmosphere. To an excellent approximation the equation of radiative transfer for a slightly lossy medium is

$$T_B(v) = T_0 e^{-\tau(v)} + \int_0^{z_{max}} T(z) \exp\left[-\int_0^z \alpha(z) dz\right] \alpha(z) dz \quad (3)$$

where scattering and variations in index of refraction have been neglected, and the variables are as defined in the following text. The equation loses validity primarily in the presence of relatively large particles like raindrops or snowflakes, and at 1-mm wavelength in the presence of some clouds. In (3), $\alpha(z)(m^{-1})$ is the absorption coefficient of the atmosphere, and $\tau(v)$ is its integral; i.e., the total opacity of the atmosphere. Equation (3) expresses the fact that the brightness temperature in any given direction is the sum of the background radiation and the radiation emitted at each point along the ray trajectory, each component attenuated by the intervening atmosphere. The equations of radiative transfer with and without scattering are discussed by Chandrasekhar [6] and are related to radio astronomy by Shklovsky [7].

In certain cases the equation of radiative transfer is more appropriately expressed in matrix form. This form is desirable, for example, when describing the effects of Zeeman-split resonance lines upon the flow of polarized radiation. One such formulation was developed and applied by Lenoir [8], [9] to 5-mm wavelength measurements of the mesospheric temperature profile.

2) *Opacity Expressions for Atmospheric Constituents:* The absorption spectrum of the atmosphere is dominated by the H_2O resonance at 22.235 GHz and the O_2 complex near 60 GHz. Strong resonances also occur at frequencies above 100 GHz. Other resonant constituents contribute only weakly.

A general reference for microwave spectroscopy is Townes and Schawlow [10] and good references for general atmospheric and surface effects include Stratton [11] and Kerr [12]. Expressions for the absorption coefficients of atmospheric constituents are usually formed by empirically choosing constants in the quantum-mechanical formulation for opacity in order to provide the best agreement with experiment. If experimental verification of the absorption coefficient expressions under all possible conditions were practical, one could dispense with quantum mechanics and electromagnetism entirely. The degree to which the absorption coefficients are presently based upon theory rather than upon experiment varies considerably depending upon the constituents and the atmospheric conditions.

In the case of the oxygen complex near 5-mm wavelength the most widely used absorption coefficient is that of Meeks and Lilley [13] who revised and updated the expressions developed by Van Vleck [3]. Gautier and Robert [14] and Lenoir [15] extended these expressions to include Zeeman splitting appropriate above 40-km altitude. The absorption coefficient was determined using the theoretical line-shape factor of Van Vleck and Weisskopf [16], and those linewidth parameters and line frequencies which were measured for the stronger lines. The linewidths have been measured at pressures near 1 atm and at low pressures. The dependence of linewidth on pressure and temperature has also been measured. A complete bibliography by Rosenblum [17] references the literature on microwave absorption by oxygen and water vapor up to 1961. Although much experimental work has been done, there is some need for still more

precise laboratory measurements, particularly of atmospheric compositions over the full range of temperatures and pressures of meteorological interest.

The absorption coefficient of oxygen in the atmosphere can also be tested by direct measurement of antenna temperatures near 5-mm wavelength. Such measurements have been made from both ground-based and balloon-borne radiometers. The most recent such measurements are those of Lenoir et al. [18]. They examined the 9^+ resonance line at 61.151 GHz with a three-channel microwave radiometer mounted on balloons which flew to altitudes of 35 km. Observations were made at zenith angles of 60°, 75°, 120°, and 180°, and at frequencies separated from 61.151 GHz by ±20, ±60, and ±200 MHz. The most precise tests of the theoretical opacity expressions are those measurements made looking upward. In this case differences between the theoretical and experimental values of atmospheric opacity as small as 5 percent could be detected in certain regions of the atmosphere. No discrepancies this large were noted 60 and 200 MHz from resonance when the balloon was in the altitude region 25 to 32 km. One such data set from Lenoir et al. [18] is shown in Fig. 1. The experiments were less sensitive to opacity uncertainties in other regions of the atmosphere or spectrum, but in these regions the differences between the theoretical and experimental brightness temperatures were generally less than 5°K, the approximate experiment accuracy.

Sensitive solar absorption measurements at 53.4 to 56.4 GHz by Carter et al. [19] have permitted the Van Vleck-Weisskopf line shape to be refined slightly.

Water vapor has transitions at 22.237 and 183.3 GHz, in addition to many transitions at higher frequencies. The opacity expressions for the 22-GHz line were developed by Van Vleck [4], [12], and were refined by Barrett and Chung [20] on the basis of the experimental findings of Becker and Autler [21] and the theoretical calculations of Benedict and Kaplan [22]. Relatively good agreement between theory and experiment was obtained by combining the Van Vleck and Weisskopf [16] line shape with a nonresonant term which corresponds to contributions from the far wings of all the resonances at other frequencies. The magnitude of the nonresonant term was selected to provide the best agreement with the measurements of Becker and Autler, which were made at pressures near 1 atm. Gaut [23] and Croom [24] have also developed expressions for the 22-GHz absorption coefficient.

Gaut [23] has developed an expression for the absorption coefficient near the 183.310-GHz water vapor resonance. He included the effects of several neighboring lines by using in part the line strength calculations of King et al. [25], the Van Vleck-Weisskopf line shape, and measurements of Rusk [26], Frenkel and Woods [27], and Hemmi [28]. Croom [29] has done similar calculations. The review and bibliography by Rosenblum [17] is a useful reference for work published prior to 1961.

Direct measurements of the atmosphere have been made primarily near 22 GHz. Most of these measurement pro-
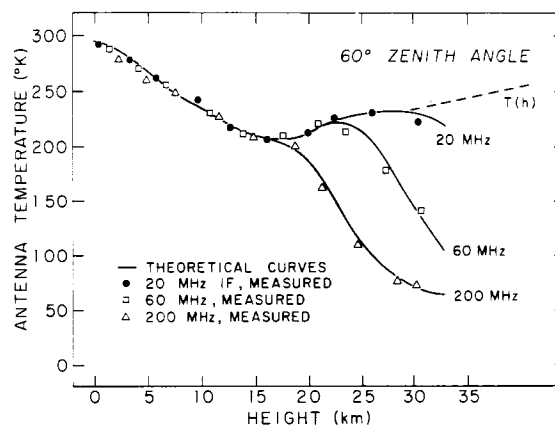

Fig. 1.   Experimental and theoretical values of antenna temperature at three IF frequencies for a 61.151-GHz balloon-borne radiometer. (After Lenoir et al. [18])
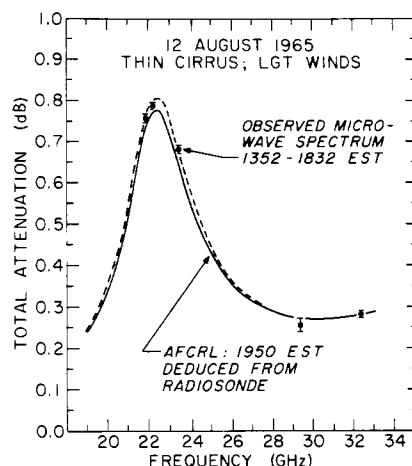

Fig. 2.   Zenith attenuation spectrum deduced from direct microwave measurements; and spectrum computed using temperature and humidity data from a radiosonde launched near the radiometer. (After Gaut [23])

grams have been handicapped because atmospheric water vapor varies somewhat more rapidly than the observing frequency can be changed, or more rapidly than accurate correlative measurements can be made. The remedy is improved instrumentation and stable meteorological conditions. An extensive series of observations has been made with a five-frequency radiometer by Staelin [30] and Gaut [23]. Five frequencies were observed simultaneously in absorption against the sun and permitted opacity measurements with an approximate accuracy of 0.02 dB or less than 5 percent of the total opacity. Meaningful comparison of the measured opacity spectrum and that spectrum expected on the basis of simultaneous radiosondes was possible only on days characterized by very stable meteorological conditions. One such comparison made by Gaut [23] is illustrated in Fig. 2. Examination of nine spectra measured under these stable conditions indicate that the theoretical expressions of Barrett and Chung [20] are accurate to better than 5 percent for typical atmospheric conditions.

Ozone has many spectral lines at microwave frequencies,

but because of the low abundance of ozone these lines are difficult to detect. Barrett [5] listed resonances of ozone at frequencies (GHz) of 9.201, 10.226, 11.073, 15.116, 16.413, 23.861, 25.300, 25.511, 25.649, 27.862, 28.960, 30.052, 30.181, 30.525, 36.023, 37.832, 42.833, 43.654, 96.229, 101.737, and 118.364. Absorption coefficient expressions have been developed by Caton et al. [31], Caton et al. [32], and Weigand [33]. These theoretical expressions are based upon line frequencies and line strengths calculated by Gora [34] and upon the Van Vleck–Weisskopf line-shape assumption. At present five resonances in the terrestrial atmosphere have been observed. Mouw and Silver [35] observed the 36.025-GHz line in absorption against the sun, Caton et al. [31] observed the 37.836-GHz line in absorption and the 30.056-GHz line in emission, Barrett et al. [36] observed the 23.861-GHz line in emission, and Caton et al. [32] observed the 101.737-GHz line in both emission and absorption. For spectral resolution of a few megahertz, the line amplitudes in emission at zenith are generally a few tenths of a degree Kelvin except for the line at 101.737 GHz, which had an amplitude of a few degrees. The most precise line measurement was that made at 101.737 GHz by Caton et al. [32], and their figure showing the line observed in absorption against the sun at 64° zenith angle is reproduced here in Fig. 3. In order to match the theoretical and experimental curves they found it necessary to multiply the amplitude of the theoretical line by a factor of 1.5. It is uncertain whether this difference is due to errors in the opacity expression or errors in the assumed model atmosphere. More measurements of ozone would be very helpful.

Clouds exhibit no resonances in the microwave region of the spectrum but instead absorb by nonresonant processes.

Mie [37], Stratton [11], and others have developed expressions for the absorption and scattering cross sections of dielectric spheres, and Ryde and Ryde [38] and Haddock [39] have then used the dielectric constants for water given by Saxton and Lane [40] in order to compute the microwave absorption coefficients for clouds and rain. Goldstein (in Kerr [12]) and Atlas et al. [41] have reviewed and summarized much of this work. These equations can be extended to include snow and ice clouds through use of the refractive index of ice measured by Cumming [42]. These results were summarized by Atlas et al. [41] and are reproduced here in Table I. These studies show that scattering in clouds can generally be neglected if the wavelength is more than 30 times the droplet diameter.

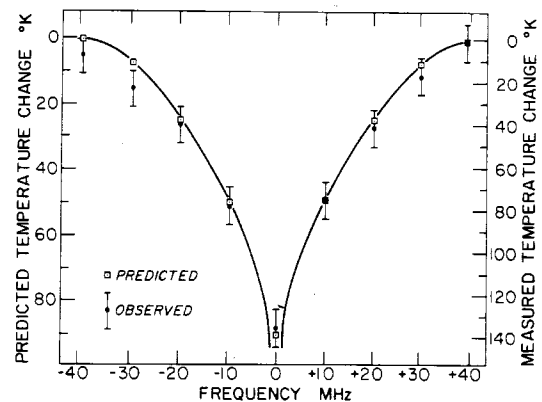Such theoretical calculations are approximate [12] be-

Fig. 3. Solar absorption spectrum showing the 101.7 GHz resonance of atmospheric ozone. The predicted values were increased by a factor of 1.5 to match the measured values. (After Caton et al. [32])

TABLE I

Working Values of Attenuation in dB · km^{-1} (one way)

Absorber	Temp. (°C)	3.2 cm	1.8 cm	1.24 cm	0.9 cm
Rain* (R in mm · h^{-1})	18†	0.0074R$^{1.31}$	0.045R$^{1.14}$	0.12R$^{1.05}$	0.22R$^{1.00}$
Snow*	0	3.3 × 10^{-5}R$^{1.6}$ 68.6 × 10^{-5}R‡	3.32 × 10^{-4}R$^{1.6}$ 12.2 × 10^{-4}R‡	1.48 × 10^{-3}R$^{1.6}$ 1.78 × 10^{-3}R‡	5.33 × 10^{-3}R$^{1.6}$ 2.44 × 10^{-3}R‡
(R in mm · h^{-1} of melted water)	−10	3.3 × 10^{-5}R$^{1.6}$ 22.9 × 10^{-5}R‡	3.32 × 10^{-4}R$^{1.6}$ 4.06 × 10^{-4}R‡	1.48 × 10^{-3}R$^{1.6}$ 0.59 × 10^{-3}R‡	5.33 × 10^{-3}R$^{1.6}$ 0.81 × 10^{-3}R‡
	−20	3.3 × 10^{-5}R$^{1.6}$ 15.7 × 10^{-5}R‡	3.32 × 10^{-4}R$^{1.6}$ 2.80 × 10^{-4}R‡	1.48 × 10^{-3}R$^{1.6}$ 0.41 × 10^{-3}R‡	5.3 × 10^{-3}R$^{1.6}$ 0.56 × 10^{-3}R‡
Water cloud	20	0.0483 M	0.128 M	0.311 M	0.647 M
	10	0.0630 M	0.179 M	0.406 M	0.681 M
(M in g · m^{-3})	0	0.0858 M	0.267 M	0.532 M	0.99 M
	−8	0.112 M (extrapolated)			
Ice cloud	0	2.46 × 10^{-3} M	4.36 × 10^{-3} M	6.35 × 10^{-3} M	8.7 × 10^{-3} M
	−10	8.19 − 10^{-4} M	1.46 × 10^{-3} M	2.11 × 10^{-3} M	2.9 × 10^{-3} M
(M in g · m^{-3})	−20	5.63 × 10^{-4} M	1 × 10^{-3} M	1.45 × 10^{-3} M	2 × 10^{-3} M

* These are empirical equations. For the more exact relations on which they are based, see Atlas et al. [41].

† The effect of temperature is discussed in Atlas et al. [41]. The effect of nonsphericity on Q_s and Q_e has been neglected.

‡ As long as snowflakes are in the Rayleigh region. A value of R = 10 or R$^{1.6}$ = 39 is an upper limit for snowfall rates.

cause they must be based upon some assumed distribution of particle sizes, shapes, etc. The expressions are less sensitive to drop size at the longer wavelengths. The expressions are best tested by field measurements. Goldstein [12] has reviewed several efforts to correlate rainfall rate with path loss measured along a short path. These measurements at wavelengths ranging from 0.62 to 3.2 cm are all within a factor of 2 of the predicted average attenuation. Emission spectra have been measured with a ground-based five-channel microwave radiometer observing at frequencies from 19.0 to 32.4 GHz [43]. These spectra showed good agreement with the theoretical spectrum shapes, even through all but the heaviest rainfall. Data obtained at 30° elevation are compared with theoretical spectra in Fig. 4. The cloud types inferred from these spectra were consistent with those characteristic of frontal passages.

3) *The Terrestrial Surface:* The terrestrial surface both emits and reflects radio waves, and the degree to which it does either is determined primarily by the surface dielectric constant and the detailed structure of the surface. In some cases the emission and reflection coefficients calculated for smooth surfaces are good approximations [11]. This is true for calm ocean and smooth homogeneous dirt surfaces, especially at longer wavelengths. Gaut [23] and Marandino [44] have calculated the emissivity of smooth water for a number of temperatures and wavelengths, and Marandino has made similar calculations for several solid surfaces.

Three interesting properties of the ocean surface are worthy of note: 1) the reflectivity is high, near 0.6, 2) the dielectric constant, and hence the emissivity, varies with temperature, and 3) the brightness temperature of the ocean surface is a function of surface roughness, which in turn is correlated with wind velocity. The high reflectivity results in a very low surface brightness temperature over most of the microwave spectrum, and thus spectral lines like H_2O or O_3 can be seen in emission from space. The temperature dependence of the emissivity results in certain combinations of sea surface temperature and frequency having a surface brightness temperature independent of surface kinetic temperature, and at other combinations the dependence can be moderately strong. For water temperatures near 285°K this temperature dependence is weak for wavelengths of 1 and 20 cm, and is stronger near wavelengths of 3 cm. Yap [45] and Stogryn [46] have calculated the dependence of surface brightness temperature upon equivalent wind speed, based upon the surface-slope statistics developed by Cox and Munk [47]. For example, Yap computed the effect at 3-cm wavelength at nadir to be approximately 0°K per knot equivalent wind speed, and 60° nadir angle to be 0.5°K for $E_\perp$ polarization and 0°K for $E_\parallel$ polarization. At wind speeds over 25 knots white caps, foam, and spray become important and the brightness temperature of the sea may increase 15°K or more.

Since the terrestrial surface is difficult to analyze analytically, much emphasis must be placed on field measurement programs. Measurements by Porter [48] of smooth asphalt and concrete are in reasonable agreement with theory, as

are mapping measurements by Catoe *et al.* [49]. Measurements of rough surfaces have also been made, and qualitative agreement with intuition has been obtained. Very few well-calibrated measurements have been made.

B. Mathematics of Data Interpretation

One of the central problems in remote sensing is conversion of the measurements into estimates of the desired atmospheric parameters with the smallest possible error. It is often called the inversion problem because it can be interpreted as the problem of inverting the equations of radiative transfer. There are several major approaches which have been taken toward solving this problem. These approaches include 1) the trial and error or library technique, 2) linear analytical procedures, 3) nonlinear analytical procedures, 4) linear statistical methods, and 5) nonlinear statistical methods.

The trial and error or library procedures, as the names imply, simply involve calculation of a large number of theoretical values for the measurements, and selection of that model atmosphere which provides the best agreement with the measurements actually obtained. Although the
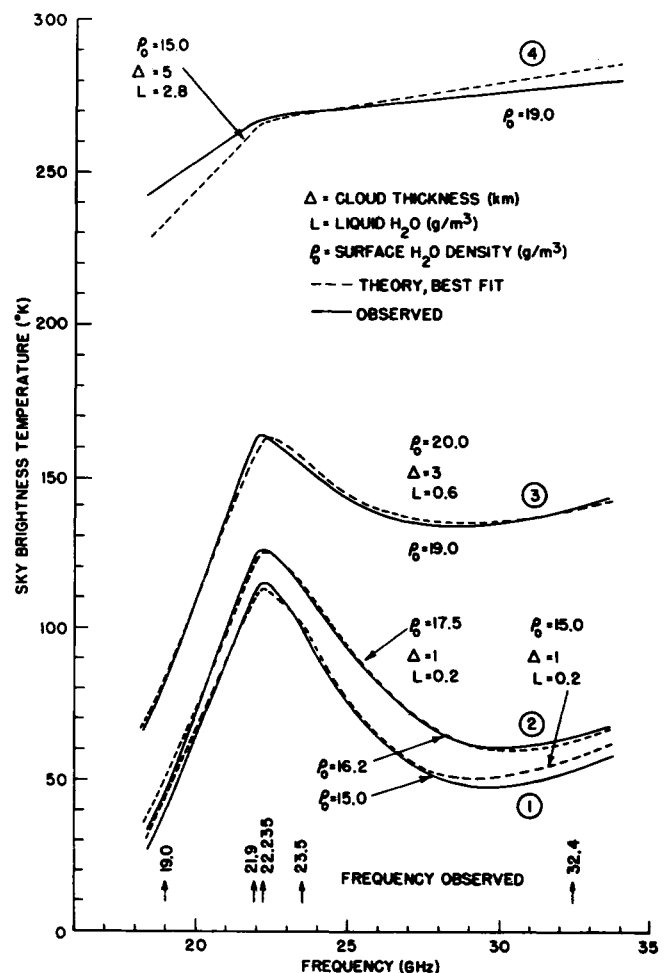

Fig. 4. Theoretical and experimental atmospheric emission spectra obtained at 30° elevation angle during a frontal passage. (After Toong [43])

method is useful because of its conceptual simplicity, there are few inversion problems for which this technique produces completely useful results. Examples include the inversion of Toong [43] and most studies of the atmospheres of other planets. These are cases where a priori data is not available or where accurate correlative measurements were not feasible.

Linear analytical procedures include those of King [50], Fow [51], and others. These methods consist primarily of the solution of a set of simultaneous linear equations which relate N atmospheric parameters to N measured parameters. Writing these equations usually involves linearizing the applicable equations of radiative transfer. These equations are then solved simultaneously to yield estimates for the unknown parameters. Because this may involve the inversion of a nearly singular matrix, it is necessary to have data that is not noisy or to incorporate boundary conditions which lead to a less singular matrix. If the matrix to be inverted is not singular, then the method is often satisfactory.

Nonlinear analytical inversion procedures are similar to the linear procedures, except that nonlinear equations are to be solved. For example, King [52] considered the problem of approximating the atmospheric temperature profile by a set of slabs of varying thickness, or by a set of ramps, and Chahine [68] explored iteration procedures.

Linear statistical methods are similar to the linear analytical techniques, except that the final matrix which multiplies the data vector to yield the parameter vector is selected so as to minimize some error criterion, such as the mean-square estimation error. There are several approaches to the problem. One approach is that of Twomey [53], [54], in which the mean-square error between the true and estimated parameter vectors is minimized by heuristic adjustment of a smoothing parameter which represents the degree to which the estimate is smoothed and biased toward the a priori mean. This bias toward the a priori mean avoids inversion of singular matrices.

Perhaps a more elegant technique is that applied by Rodgers [55] to inversions of atmospheric temperature profiles at infrared wavelengths. In this procedure, also discussed by Deutsch [56], Strand and Westwater [57], and others, the mean-square error between the estimated and true parameter vector is minimized without any heuristic parameters. A complete set of a priori statistics is required to implement the procedure, however. The technique can be described simply as follows. Let the measured data and the desired parameters be represented by the column vectors d and p, respectively. In order to reduce the dimensionality of p, a statistically orthogonal set of basis functions for p-space is sometimes sought, as discussed by Rodgers [55] and others. Let p^* be the estimate of p based on a particular measured d, and let p^* be computed by multiplying d by the matrix D, where D is not necessarily a square matrix. The optimum matrix D may then be computed by finding that D which minimizes the mean-square error, $E[(p^*-p)^t(p^*-p)]$, where E is the expected-value

operator and the superscript t means transpose. The optimum D can be shown to be given by

$$D^t = C_d^{-1}E[dp^t] \qquad (4)$$

where C_d is the data correlation matrix, $E[dd^t]$. This procedure is equivalent to multidimensional regression analysis. In some cases the matrix C_d is sufficiently singular to degrade the inversion. In this case, as observed by Waters and Staelin [58], the vector d may be transformed to d' such that $E[d'd'^t]$ is diagonal. It can be shown that d' is $R^t d$, where R^t is the transpose of the matrix formed from the normalized column eigenvectors of C_d. The estimate p^* then is given by $D'd'$. Those elements of d' corresponding to diagonal terms in $C_{d'}$ less than the computational noise level can then be discarded.

Linear statistical estimation is optimum in a least-square sense only in special circumstances. The procedure of Rodgers [55] is optimum if the equations of radiative transfer are linear, and the parameter variations and the instrument errors are both jointly Gaussian random processes. In general these conditions do not apply, and there is room for improvement. For example, in the infrared region of the spectrum the Planck function is inherently a nonlinear function of atmospheric temperature. Even in the microwave region where the Planck function is linear, the equations of radiative transfer are somewhat nonlinear. In addition, the parameter statistics are seldom jointly Gaussian, although they often are approximately so. For nonlinear or non-Gaussian problems the optimum inversion procedures are generally nonlinear.

One quite general nonlinear statistical estimation procedure is Baye's estimate, as described for example by Helstrom [59]. The difficulty is that numerical evaluation of integrals over the parameter space can be impossibly time-consuming for estimation problems involving several data points and many parameters. A more practical technique is the nonlinear estimation procedure outlined by Staelin [60] and Waters and Staelin [58]. This technique is similar to the linear statistical technique described above, except that the data vector d is replaced by the vector $\phi(d)$, where $\phi_i(d)$ is any arbitrary function of d. This technique permits most nonlinear relations between parameters and data to be inverted, and avoids the need for iteration which is sometimes employed with the linear procedures to obtain some of the benefits of nonlinearity.

C. Instrumentation

The sensors used for microwave meteorology are generally adaptations of systems developed for radio astronomy, a field in which receiver development is quite active. The major problem areas include sensitivity, absolute accuracy, spectral response, and directional response. In addition, each application has constraints of cost, size, weight, power, reliability, and operational simplicity.

Receiver sensitivity may be characterized by the receiver noise temperature T_R, the bandwidth B, and integration time τ, a constant α which is usually in the range 1–3, and

the equivalent rms fluctuations at the receiver input ΔT_{rms}. It can be shown [61] that

$$\Delta T_{rms} = \frac{\alpha(T_A + T_R)}{\sqrt{B\tau}} \,^\circ K. \qquad (5)$$

This equation can be used to estimate an ultimate limit to receiver sensitivity. For example, a radiometer in space viewing the earth will see an antenna temperature of approximately 300°K. For a noiseless receiver with 1-second integration, RF bandwidth 10^8 Hz, and α equal 2, then ΔT_{rms} is 0.06°K. If 1°K sensitivity is sufficient, then an integration time as short as 0.004 second may be used. These limits have a strong bearing on the ultimate spatial resolution and coverage which can be obtained by radiometers in space. For example, such a receiver in earth orbit at 1000-km altitude could have spatial coverage no better than 50 spots per mile of ground track, with 1°K-receiver sensitivity.

Although the receiver noise temperature T_R is not zero, the sensitivity of receivers is rapidly improving due to the development of improved solid-state components. At wavelengths longer than 3 cm receiver noise temperatures T_R of less than 150°K can be obtained with solid-state parametric amplifiers, and this performance is being extended to wavelengths near 1 cm. With masers receiver noise temperatures lower than 40°K have been obtained in operational systems near 20-cm wavelength. At wavelengths shorter than 3 cm the most common type of receiver is the superheterodyne. These systems have noise temperatures ranging from several hundred degrees at 3-cm wavelength to perhaps 20 000°K at 3-mm wavelength. Recent improvements in Schottky-barrier diodes show promise of reducing superheterodyne noise temperatures to a few hundred degrees for wavelengths as short as 5 mm. Progress in this area is so rapid but unpredictable that planning more than five years in the future is difficult.

The absolute accuracy of most radiometers is generally much less than could be obtained with care. Perhaps the most careful measurements ever made were those performed to measure the cosmic background radiation, as described by Penzias and Wilson [62], Wilkinson [63], and others. In these experiments absolute accuracies of approximately 0.1 to 0.2°K (rms) were obtained for antenna temperatures of approximately 6°K. Since the calibration problem becomes simpler as the antenna temperature approaches the physical temperature of the radiometer, such accuracies are obtainable in situations of meteorological interest. Absolute accuracies of 1°K are readily obtainable without great care.

Almost any arbitrary spectral response can be obtained with a microwave radiometer, although most parametric or other low-noise amplifiers have instantaneous bandwidths less than approximately 200 MHz. Except for limitations imposed by the spectral response of low-noise amplifiers, bandwidths ranging from 1 to 1×10^{10} Hz could be obtained over most of the microwave region of the spectrum. Receivers capable of observing 1 to 400 spectral

intervals simultaneously have been built, in addition to single-channel frequency scanning radiometers. For accurate observations of spectral lines the multichannel radiometers generally are more accurate and permit shorter time variations to be monitored.

The directional response of antennas varies considerably depending upon wavelength and antenna size. The half-power beamwidth of most antennas is approximately 1.3 λ/D radians, where λ is the wavelength and D is the antenna diameter. Thus a 5-mm wavelength radiometer with a 1-m antenna could resolve 7-km spots from a 1000-km orbit. Still higher resolution could be obtained, but mechanical tolerances restrict most antennas to beamwidths greater than 1 to 5 minutes of arc. A second important property of an antenna is its sidelobe level, or the degree to which it is sensitive to radiation incident upon the antenna from directions outside the main beam. The fraction of energy accepted from outside the main beam of an antenna is called the stray factor, which varies between 0.05 and 0.4 for most antennas. Low sidelobes and stray factors are obtained at the expense of antenna size, although the antenna diameter seldom needs to be more than doubled to obtain reasonable performance. Most such low sidelobe antennas must be custom-made, and such antennas are seldom used, although they could improve many meteorological experiments.

Some applications require scanned antennas. These antennas can be mechanically or electrically scanned. The advantages of mechanical scanning include a superior multifrequency capability, lower antenna losses, and electronic simplicity. Electrically scanned antennas are more compact, need have no moving parts, and can scan more rapidly. A 19-GHz electrically scanned antenna system proposed for space flight has an antenna beamwidth of 2.6°, stray factor of 0.08, an insertion loss of 0.6 dB, a scan angle of $\pm 50°$, and is 18 by 18 by 3 in. The instrument has operated in aircraft over various types of terrain and meteorological conditions [49].

Reduction of size, weight, and power is expensive, and is warranted primarily for space experiments. Examples include the two-frequency radiometer which successfully observed Venus from the Mariner-2 space probe [64], and a single-frequency 5-mm wavelength radiometer in earth orbit. The Mariner-2 radiometer weighed 20 lb and consumed 5 W average power and 10 W peak power. The 5-mm wavelength radiometer weighed 16 lb, consumed 42 W average power, and had a volume of 312 in^3. Substantial reductions in size, weight, and power are expected over the next ten years.

III. METEOROLOGICAL APPLICATIONS OF PASSIVE MICROWAVE SENSING

Microwave experiments can be categorized in several different ways. Here they have been divided into 1) temperature profile measurements, 2) composition measurements, and 3) surface measurements. A review of several possible meteorological experiments from space is contained in a report edited by Ohring [65].

A. Measurement of the Atmospheric Temperature Profile

The oxygen complex centered near 60 GHz offers opportunities to measure atmospheric temperature profiles from space or from the ground. This is so because the mixing ratio of oxygen in the terrestrial atmosphere is quite uniform and time invariant, and because the attenuation of the atmosphere varies with frequency from nearly zero to over 100 dB. The possibilities for such temperature profile measurements were first explored by Meeks and Lilley [13] and have been extended by Lenoir [9] to higher altitudes. Westwater and Strand [66] have applied statistical estimation techniques to ground-based probing of the atmosphere and Waters and Staelin [58] have applied similar techniques to space-based measurements.

Meeks and Lilley [13] cast the expression for brightness temperature T_B in the form of a weighting function integral. where $W(h, v)$ is the weighting function and $T(h)$ is the atmospheric temperature profile. That is,

$$T_B(v) = \int_0^\infty T(h)W(h, v)dh + T_0 e^{-\tau(v)} \qquad (6)$$

where $T_0 e^{-\tau}$ is the contribution of the background temperature. The weighting functions reveal the extent to which the brightness temperature measured at any particular frequency is sensitive to the kinetic temperature as a function of altitude. Lenoir [15] has calculated many weighting functions appropriate to space-based microwave radiometers, and some of these are shown in Fig. 5. The weighting functions above 50-km altitude are polarization dependent and vary in a predictable way with the terrestrial magnetic field. Parameters for several weighting functions computed by Lenoir [15] are listed in Table II. Examination of the half-power widths Δh of these weighting functions indicates that altitude resolution of several kilometers can be obtained, depending upon the receiver sensitivity.

Waters and Staelin [58] have applied statistical estimation techniques to the problem of inverting such microwave data. An example of the inversion accuracy is shown in Fig. 6, where the a priori standard deviation in the temperature is compared to the standard deviation obtainable with a seven-channel space-borne microwave radiometer of $1°K$ sensitivity. The six temperature weighting functions peaked at 4, 12, 18, 21, 27, and 31 km. One water vapor channel was also incorporated. When the satellite is over ocean, water vapor can be measured and used to improve the temperature estimates because temperature and humidity are correlated. This effect is shown in Fig. 6. If the temperature profile can be measured with an accuracy of 2 to $3°K$ on a global scale, then such microwave systems would be very useful for the collection of synoptic meteorological data.

The height resolution of the radiosondes was 0.5 km, much less than the width of the weighting functions. When the inferred $T(h)$ and the true $T(h)$ used for comparison were each smoothed by convolution with an 8-km Gaussian, then the error performance was improved, as shown in Fig. 7. Thus average atmospheric temperatures over 5 to
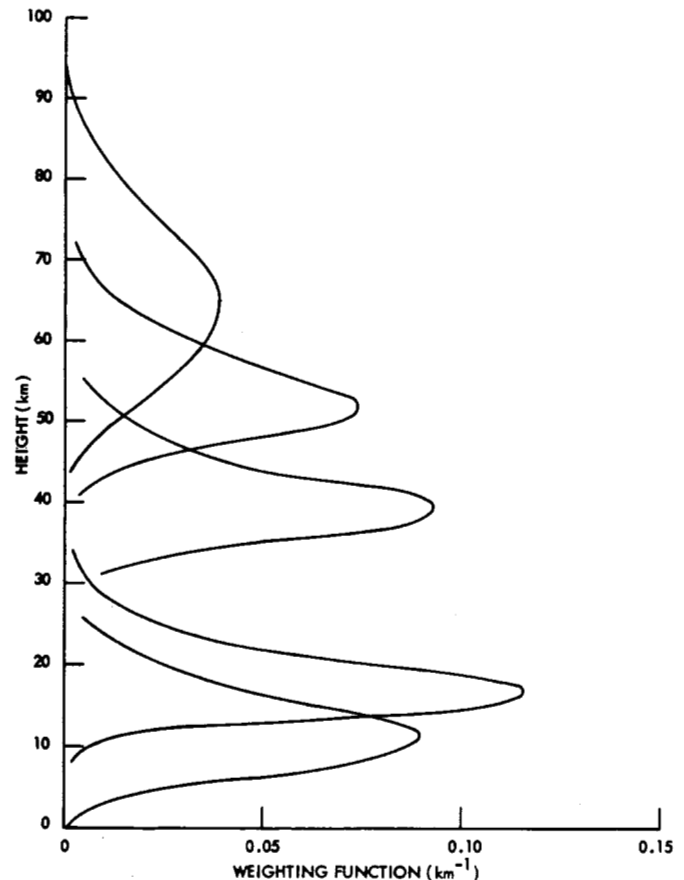

Fig. 5. Temperature weighting functions for nadir observations from space. These weighting functions each correspond to different frequency bands near 60 GHz. (After Lenoir [15])

TABLE II

WEIGHTING FUNCTIONS FOR SOUNDING THE ATMOSPHERIC TEMPERATURE PROFILE

v_0 (GHz)	W (MHz)	h_0 (km)	Δh (km)
64.47	200	12	11
60.82	200	18	7
58.388	30	27	9
60.4409	2.5	40	12
60.4365	1.0	50	20
60.5685 equator pole	1.5	60	21
		54	26
60.4348 equator pole	1.5	73	20
		66	26

10 km altitude can be inferred more accurately than can temperatures of narrower regions.

The effects of clouds and the terrestrial surface on such measurements can be estimated. In the preceding example only the weighting function which peaks at 4 km interacts appreciably with the terrestrial surface or with clouds. If the satellite is over land then approximately 15 percent of the received radiation is received from the land, of which perhaps 95 percent represents the physical temperature of the land, and 5 percent is sky reflections, which have an
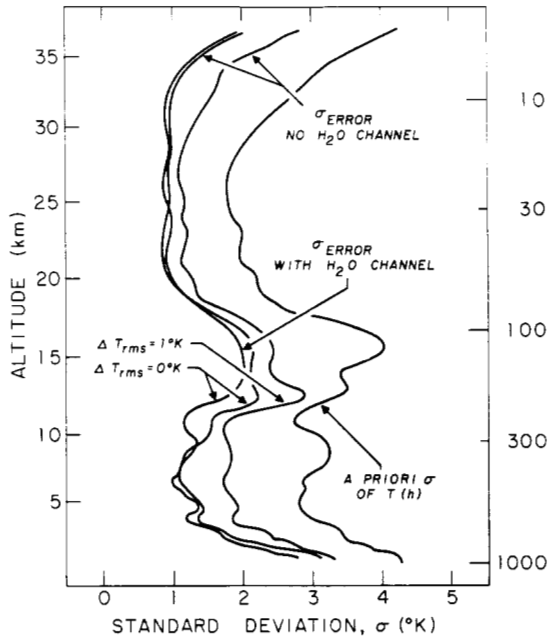
Fig. 6. Results of 100 linear temperature profile inversions showing a priori and a posteriori standard deviation for 0°K and 1°K rms receiver noise. The radiometer was assumed to be in space viewing nadir over ocean at 53.60, 58.39, 59.30, 60.82, 62.46, and 64.47 GHz in the oxygen band, and 22.235 GHz in the water vapor band. The inversion error was evaluated for 100 summer radiosondes from Peoria, Ill., having a height resolution of 0.5 km.
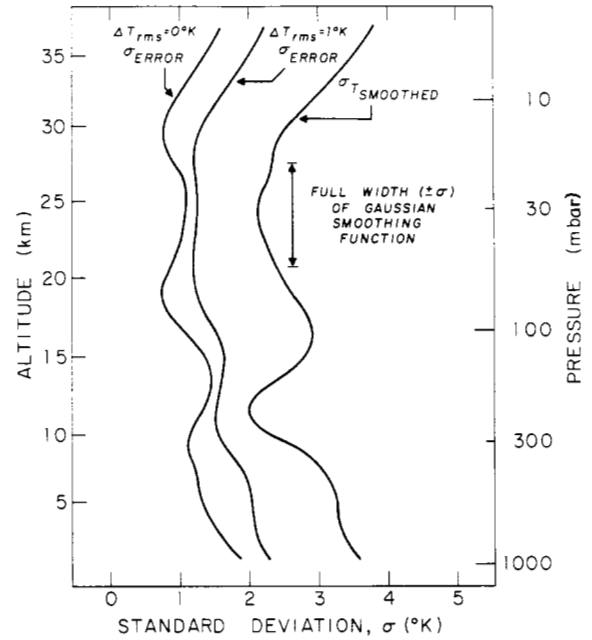
Fig. 7. Results of 100 linear temperature profile inversions using the same data used in preparation of Fig. 6. The inversion error was evaluated for a height resolution of 0.5 km after the inferred $T(h)$ and the true $T(h)$ were each convolved with a Gaussian of width 8 km.

effective temperature near 230°K. Thus a priori knowledge of the land temperature with 5°K rms uncertainty, plus knowledge of the emissivity within 1 percent rms reduces this contribution to the error in inferred atmospheric temperature to 1°K rms. Direct measurement of the surface brightness temperature at longer wavelengths can reduce this error still further. The effects of ice clouds are negligible, and even in the presence of heavy water clouds the error is small. For example, the heaviest nonraining cloud observed by Toong [43] would have an approximate opacity of 1/2 at 5-mm wavelength, and thus would contribute an approximate error of less than 3°K, assuming the cloud were centered at 3-km altitude and that it were 20° cooler than the surface. This same heavy cloud over ocean would have an even smaller effect because the cloud temperature in this case would be even closer to the brightness temperature flux moving upward at 3-km altitude. Thus even this heavy water cloud, approximately equivalent to a cumulus mediocris containing 0.18 g/cm² H_2O, would introduce no more than a few degrees error, even if it filled the entire antenna beam. Of course, if weighting functions were used which peaked nearer the surface, or if the bulk of the cloud were at much higher altitudes, then the effect could be larger.

Ground-based radiometers yield weighting functions which are quite different from those obtained for space-based measurements. These weighting functions are approximately exponentials with scale heights which depend upon the atmospheric opacity. This form of weighting function yields excellent height resolution near the observer,

but the resolution is degraded at distances beyond 5 to 10 km. Westwater and Strand [66] have calculated the errors expected for this example and find that for altitudes 0 to 10 km the rms errors range from 1.5°K to 4°K, respectively for 1°K receiver noise. Cloud effects for upward-looking radiometers are more severe than for those systems looking down because the equivalent temperature of space is much colder and therefore offers more contrast to clouds than does land. The fast response of microwave radiometers plus their ability to scan and to observe continuously may enable ground-based microwave radiometers to provide meteorological information of a type not obtained before.

B. Measurement of Composition Profiles

Composition measurements are usually made in semi-transparent regions of the microwave spectrum where the spectrum is more sensitive to the distribution of absorbers in the atmosphere than to the temperature profile. For those constituents with resonances the problem of determining the distribution profile can also be expressed in terms of weighting functions. For example, measurements of a spectral line in absorption against the sun can yield $\tau(v)$. If those contributions to $\tau(v)$ from extraneous constituents are subtracted, then the remaining $\tau_r(v)$ for the constituent of interest can be expressed as

$$\tau_r(v) = \int_0^\infty \rho(h)W(v, h)dh \qquad (7)$$
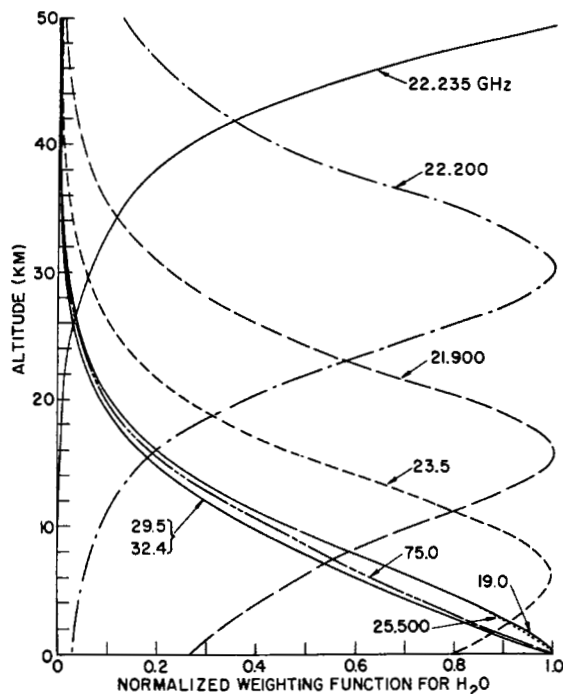
where

$$W(v, h) = \alpha(v, h)/\rho(h)$$

Fig. 8. Normalized weighting functions for interpreting water vapor opacity measurements in the terrestrial atmosphere. (After Staelin [30])

TABLE III

INVERSION PERFORMANCE FOR GROUND-BASED RADIOMETER VIEWING
ZENITH AT 20.0 AND 22.0 GHz

Water vapor altitude	Water vapor statistics (g/cm²)		Water vapor inversion errors (g/cm²)	
	mean	σ	$\sigma(\Delta T_{rms}=0°K)$	$\sigma(\Delta T_{rms}=1°K)$
0–9.5 km	3.19	2.03	0.02	0.08
0–2 km	1.94	1.21	0.14	0.20
2–4 km	0.83	0.55	0.13	0.13
4–9.5 km	0.42	0.38	0.11	0.16

TABLE IV

INVERSION PERFORMANCE FOR SPACE-BASED RADIOMETER VIEWING NADIR
AT 22, 31, 53.6, 60.8, AND 64.5 GHz, OVER SMOOTH OCEAN

Water vapor altitude	Water vapor statistics (g/cm²)		Water vapor inversion errors (g/cm²)	
	mean	σ	$\sigma(\Delta T_{rms}=0°K)$	$\sigma(\Delta T_{rms}=1°K)$
0–9.5 km	2.09	1.34	0.09	0.11
0–2 km	1.35	0.92	0.22	0.22
2–4 km	0.51	0.35	0.14	0.14
4–9.5 km	0.23	0.15	0.09	0.09

and where $\rho(h)$ is the constituent density profile, $W(v, h)$ is the weighting function, and $\alpha(v, h)$ is the absorption coefficient of the desired constituents. These weighting functions are weak functions of temperature, pressure, and $\rho(h)$, so a priori information about these parameters can determine the weighting function to a reasonable degree of accuracy. Staelin [30] has computed such weighting functions for water vapor, as shown here in Fig. 8. Very similar weighting functions result when the expressions are written for brightness temperature seen from the ground, or brightness temperature seen from space when over ocean. This is in contrast to the weighting functions found for the atmospheric temperature profile, which are quite different when observing from space or from the surface. Because the shape of the weighting function is determined almost exclusively by the variation of the linewidth parameter with altitude, almost identical weighting function shapes would apply for O_3, OH or other trace constituents. The weighting function concept begins to break down, however, when the optical depth of the desired constituent is greater than 0.5, or when the background brightness temperature approaches the kinetic temperature of the atmosphere. Thus the weighting function concept can not readily be used to interpret the 183.3-GHz line of water vapor, nor any lines of trace constituents viewed from a spacecraft over land. Of course the development of weighting functions is not a prerequisite for use of the statistical estimation procedures described earlier. The existence of weighting functions does imply a certain degree of linearity in the estimation problem however.

Gaut [23] has applied the method of Rodgers [55] to inversion of the solar absorption measurements of water vapor at 22 GHz, and Waters and Staelin [58] have considered the problem of estimating water vapor by measuring brightness temperatures from space or from the ground. Recent preliminary calculations of Waters and Staelin are presented in Table III and IV. These calculations of estimated inversion errors were based on assumed perfect knowledge of the absorption coefficient and statistics computed from 100 radiosonde records. The results in Table III were computed for 20- and 22-GHz ground-based observations at zenith on the basis of 100 radiosondes, half from Tucson, Ariz., and half from Kwajalein Island. These calculations indicate that the integrated water vapor abundance can be determined to 0.1 g/cm². In Table IV are presented similar results for observations from space over ocean. The atmosphere statistics were based upon 100 radiosondes from Huntington, W. Va., half in winter, and half in summer. The ability to resolve the water vapor profile with 2-km resolution results primarily from the a priori statistics, and secondarily from the resolution of the weighting functions. The weighting functions provide useful results with a resolution of 5 to 10 km, depending upon measurement accuracy.

With the improved radiometric systems which should become available over the next few years, similar performance might be sought for ozone and stratospheric water vapor. The measurements of ozone were reviewed earlier in this paper. Stratospheric water vapor has tentatively been detected at 22 GHz [67]. Since no such meteorological data has been collected on the scale that passive microwaves

should permit, the data will be quite unique. Spatial structure in three dimensions plus time variations should all be accessible.

Clouds and precipitation can also be measured. Because of the nonresonant nature of their absorption, however, it is difficult to measure altitude distribution or even to distinguish clouds from precipitation. Rain and clouds might be distinguished on the basis of form and intensity, and even on the basis of spectral shape, but the measurements of Toong [43] indicate that such distinctions would be difficult to perform with any accuracy. Snow and ice might best be distinguished from water and rain on the basis of atmospheric temperature and climatology.

Nonresonant absorbers like clouds and precipitation can, however, be measured quantitatively and distinguished from water vapor or other resonant constituents. This was demonstrated theoretically by Staelin [60] and experimentally by Toong [43]. Nonresonant constituents can best be measured from ground-based radiometers or from spacecraft over ocean. The accuracies which might be obtained can only be estimated. They are best expressed in terms of equivalent water cloud densities in g/cm^2 at some nominal temperature, like $283°K$. A ground-based 0.9-cm receiver with sensitivity $1°K$ looking at zenith could detect a cloud with 0.005 g/cm^2. if the water vapor abundance were known exactly. Since the clouds must be distinguished from water vapor on the basis of spectral shape, the cloud sensitivity might be degraded to 0.01 g/cm^2. The measurement accuracy would be further degraded by uncertainties in cloud temperature, $5°K$ representing ~ 15 percent change in α.

C. Measurement of Surface Properties

Surface properties of interest include surface temperature, ground water, snow and ice cover, and sea state. Since the surface brightness temperature at long wavelengths is essentially the product of the surface emissivity and the surface temperature, the surface temperature can not be uniquely determined. If the surface brightness temperature is measured from space over a long period of time, then the surface emissivity may be averaged or calibrated out, and accurate measurements of temperature may be obtained. It is not known to what extent daily changes in emissivity may occur, but since the emissivity of most land surfaces is greater than 0.9, the variation is limited. The use of $E_\perp$ polarization (electric vector perpendicular to the plane of incidence) near the Brewster's angle may increase the emissivity further. Improvement may also be obtained by simultaneous monitoring of $E_\perp$ and $E_\parallel$ polarization so as to detect changes in emissivity and perhaps permit corrections to the inferred temperature. The presence of ground water should decrease the brightness temperature of $E_\perp$ radiation, and snow or ice should normally increase it. This is an area where more analysis and experiments are needed before performance can be accurately predicted.

Sea state may be measured from space by observing $E_\perp$ and $E_\parallel$ polarization at a nadir angle near $60°$. Since the change in brightness temperature with equivalent wind speed for winds less than 30 knots has been calculated to be approximately $0.5°K$ per knot for $E_\perp$ polarization at 3-cm wavelength, and since the accuracy of the measurement should be approximately $1°K$, the equivalent wind speed might be inferred with an accuracy of 2 knots. The analysis on which this was based neglected features like whitecaps and foam, and assumed that the ocean surface was composed of smooth facets large compared to a wavelength. Furthermore the sea surface properties depend not only upon wind speed, but also on fetch, current, surface pollution, etc. The true accuracy which might be obtained would best be determined by very carefully calibrated measurements at sea. Such measurements would be desirable not only at wavelengths where the atmosphere is nearly transparent, but also at wavelengths where the atmosphere absorbs up to one-half the radiation, because at these wavelengths that component of the radiation reflected from the sea surface into the antenna beam is quite sensitive to the surface slope probability distribution.

IV. Meteorological Relevance and Suggestions for Further Work

There are several meteorological problem areas for which passive microwave sensors have unique capabilities.

1) Microwave sensors provide the only remote sensing technique capable of measuring atmospheric temperature profiles in the presence of clouds. This may be of crucial importance to global data collection for numerical weather prediction unless new techniques are developed which permit other remote sensors, super pressure balloons, etc., to operate more effectively in the 300 to 1000-mbar region than do microwaves. Above 300-mbar microwave sensors are also a competitive technique.

2) Microwave sensors appear to be unique in their ability to measure the temperature profile above 50-km altitude. Synoptic mesospheric temperature data collected by satellite would be unparalleled as a tool for studying the mesospheric temperature structure.

3) Microwaves are unique in their ability to yield measurements of tropospheric water vapor in the presence of clouds. Although such sensors in space are effective only over ocean, the oceans cover over half the globe, and are very poorly monitored in contrast to most land masses. Even in the absence of clouds the great sensitivity of microwaves to water vapor and the ability of microwave sensors to average water vapor spatially permits measurements of integrated water vapor abundances which are competitive with and perhaps superior to radiosondes, which appear to be handicapped by aliasing errors [23]. This averaging ability and ability to operate through clouds may make such instruments valuable on the ground also.

4) Microwaves are unique in their ability to measure water vapor above the tropopause and ozone on a continuous basis. Although this is difficult and has not yet been

done, it is within the state-of-the-art. Again, until these experiments are done it is difficult to predict the meteorological significance. One might certainly hope to learn more about the distribution and variability of these constituents, and perhaps to use them as tracers for circulation in the upper atmosphere. Such experiments could be done from the surface or from space.

5) Microwaves provide a powerful tool for measuring the total liquid water content of clouds, and even though there may be some ambiguity in the presence of large particles or precipitation, the data are still quite unique. If such data could be taken with a high-resolution imaging system on board a satellite, storm cells, squall lines, etc., could be mapped with a precision not always available with optical sensors. Proper choice of wavelength would permit only very heavy clouds to be seen, or alternatively, perhaps almost all water clouds.

6) Microwaves offer promise of land temperature measurements from space. Such data are of interest in their own right, and also as an aid to determining the temperature profile of the troposphere.

7) Microwaves offer promise of yielding such surface characteristics as sea state, snow cover, ice cover, ground water, etc. More research is needed to determine the true potential of such experiments, although the sea state measurements appear quite promising.

Still other applications exist, and no doubt new ones will develop as the field of microwave meteorology grows.

Several suggestions for further work are obvious.

1) The expressions used for absorption coefficients of various atmospheric constituents should all be refined both experimentally and theoretically, particularly at millimeter wavelengths.

2) The microwave properties of the surface should be studied in a precise quantitative way in preparation for possible surface temperature measurements, sea state measurements, etc., from space.

3) The statistical inversion techniques should be improved and applied to a broader range of microwave problems where microwave sensors are accompanied by infrared or other types of sensors.

4) Efforts should continue to improve the sensitivity, accuracy, and antenna characteristics of radiometric systems, particularly at millimeter wavelengths, while reducing their size, weight, and cost.

5) Efforts to detect new spectral lines should continue as improved instruments become available.

6) Those which have been detected should become meteorological tools and studied as such, in particular, the stratospheric water vapor and the ozone lines should be observed.

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