Radio Science, Volume 13, Number 4, pages 677–685, July–August 1978

The accuracy of water vapor and cloud liquid determination by dual-frequency ground-based microwave radiometry

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(Received September 6, 1977.)

A dual frequency ground-based radiometer operating in the 1 to 1.4 cm wavelength range can provide continuous measurements of integrated water vapor and cloud liquid water. Using climatological data, the accuracy of the vapor and liquid determinations is estimated as a function of cloud amount. Limiting factors in the water determination are uncertainties in water vapor absorption coefficients and, during cloudy conditions, uncertainties in cloud temperature. For integrated water vapor content greater than 10 mm, the accuracy of the vapor determination is better than 15% for a wide range of cloudy conditions.

1. INTRODUCTION

Total precipitable water is an important component of many moisture-related processes in the atmosphere. For example, the occurrence of convective clouds and precipitation is closely related to the amount of water vapor in the layer from the surface to 400 mb [*Battan and Kassander,* 1960]. Consequently, measurements of integrated vapor have been used in the design of cloud seeding experiments [*Dennis and Koscielski,* 1969]. Continuous observations of this quantity may also be useful in operational precipitation forecasting, and in meteorological research applications such as the estimation of water vapor flux into convective cells [*Leichter and Dennis,* 1974]. Other problems that require integrated water vapor, although not necessarily in the zenith direction, include electrical path length correction [*Westwater,* 1967; *Schaper et al.,* 1970], and real-time prediction of transmission for both infrared and millimeter wave propagation.

At the present time, precipitable water V can be measured in several ways. Operationally, V can be obtained by integrating radiosonde soundings and can be estimated, between soundings, by statistical regression of surface observations [*Reitan,* 1963; *Tomasi,* 1977]. However, single wavelength radiometric observations of precipitable water, obtained during clear conditions, have indicated frequent occurrences in which the total water content changed by 50% in periods of one or two hours and during which either the surface moisture remained nearly constant [*Gurvich et al.,* 1972] or the emission showed no correlation with surface dew point temperature [*Fogarty,* 1975]. Clearly, under such conditions prediction from surface conditions is unreliable. Another measurement technique, and one that gives both good accuracy and continuity in time, uses the spectral hygrometer to infer V from the infrared attenuation of solar radiation [*Tomasi et al.,* 1974]. However, this method is strongly affected by dense clouds, requires an assumption of horizontal stratification, and is restricted to daytime. Aircraft soundings, using a microwave cavity refractometer and a temperature sensor [*Gilmer et al.,* 1965], are capable of high accuracy in point measurements, but are too expensive for routine observations and are not ideal for vertical soundings.

None of the above techniques is completely appropriate for long-term, continuous, and near all-weather operation. Because of its operational simplicity and its proven performance in such areas as long-term attenuation monitoring, microwave radiometry seems ideally suited for routine monitoring of moisture and its changes with time.

The relationship between microwave thermal emission and atmospheric moisture was first observed by *Dicke et al.* [1946]. Although most of their measurements were taken during clear conditions, they mentioned that some cumulus clouds were quite absorbing at centimeter wavelengths.

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Subsequently, *Barrett and Chung* [1962] and *Staelin* [1966] discussed the determination of profile information from multispectral emission or extinction observations. In addition, Staelin discussed the possibilities of simultaneous vapor and cloud liquid determination. These possibilities were experimentally demonstrated by *Toong and Staelin* [1970] who obtained vapor and cloud liquid from emission observations at five frequencies. In addition, the Russian literature contains many descriptions of experimental determinations of vapor and liquid [*Plechkov*, 1968; *Gorelik et al.*, 1973; *Yershov and Plechkov*, 1977]. For down-looking systems, *Rosenkranz et al.* [1972] gave accuracy estimates for radiometric moisture determination.

In spite of the large amount of work on the problem, several important questions have not been addressed in the literature. Among these are the following: What is the range of cloud amounts over which useful vapor determinations can be obtained and, hence, what degree of reliability can dual frequency systems be expected to have? What effects do errors in molecular absorption parameters have on the vapor determination, and how can these errors be minimized? What are optimum frequencies for the system?

To answer these questions we describe below our accuracy estimates of radiometric determination of liquid and vapor. These results imply that, even with present uncertainties in absorption calculation, accuracies usually better than 15% can be achieved for a wide range of cloudy conditions.

2. DETERMINATION OF INTEGRATED WATER VAPOR AND CLOUD LIQUID FROM RADIOMETRIC OBSERVATIONS

Under conditions of low attenuation (optical depth $\leqslant 1$), total absorption can be derived from atmospheric emission [*Hogg and Chu*, 1975]. This absorption can, in turn, be directly related to corresponding amounts of integrated water vapor V and cloud liquid L. As discussed by *Staelin* [1966] measurements of low attenuation at a vapor-sensitive frequency and a cloud-sensitive frequency allow separation of the two water phases. Various separation algorithms are possible [*Staelin*, 1966; *Grody*, 1976]; we briefly describe a physically transparent method in which the effect of uncertainties (both in measurement and of physical constants) can easily be evaluated.

If the total atmospheric transmission at frequency ν is written as $\exp(-\tau_\nu)$, then measurements of microwave brightness temperature $T_{b\nu}$ can be converted to this opacity τ_ν by

$$\tau_\nu = -\ln[(T_{mr} - T_{b\nu})/(T_{mr} - T_{bb})] \tag{1}$$

where T_{bb} is the cosmic background "big bang" brightness temperature equal to 2.8 K, and T_{mr} is an estimated "mean radiating temperature." For nonprecipitating clouds, we can write

$$\tau_\nu = \kappa_{V\nu} V + \kappa_{L\nu} L + \tau_{d\nu} \tag{2}$$

where $\kappa_{V\nu}$ and $\kappa_{L\nu}$ are path-averaged mass absorption coefficients of vapor and liquid, and $\tau_{d\nu}$ is the dry absorption. since microwaves interact only weakly with ice clouds [*Staelin et al.*, 1975], their effect is neglected here. From measurements at two frequencies, we can form two equations and solve for the two unknowns V and L:

$$V = (\kappa_{Lu} f_l - \kappa_{Ll} f_u)/(\kappa_{Vl}\kappa_{Lu} - \kappa_{Vu}\kappa_{Ll}) \tag{3}$$

$$L = (-\kappa_{Vu} f_l + \kappa_{Vl} f_u)/(\kappa_{Vl}\kappa_{Lu} - \kappa_{Vu}\kappa_{Ll}) \tag{4}$$

where

$$f_\nu = -\tau_{d\nu} - \ln[(T_{mr} - T_{b\nu})/(T_{mr} - T_{bb})] \tag{5}$$

for $\nu = l, u$. In (3), (4), and (5), we use the notation l and u to refer to lower (water-vapor-sensitive) and upper (liquid-water-sensitive) frequencies. Physically, f_ν is a measure of the opacity at ν from water vapor and cloud liquid. Observe that in (3), the estimate of V depends only on the ratio of κ_{Lu} and κ_{Ll} and not on their absolute values. The implication of this when measuring water vapor in the presence of light rain is discussed in the next section.

As discussed in section 3, (3)–(5) can be used to derive V and L from measurements of T_b. This first requires the calculation of mass absorption coefficients and dry attenuation from a model profile of the vertical temperature, pressure, and humidity distributions.

3. FACTORS CONTRIBUTING TO ERROR IN RADIOMETRIC DETERMINATION OF LIQUID AND VAPOR

Radiometric determination of V and L requires both the physical measurement of radiation and

TABLE 1. Calculations of mean (κ_{V_ν}) and standard deviation σ of water vapor absorption coefficient.

A. Weather ship D						
Frequency (GHz)	19.35	20.6	21.5	22.0	22.235	31.65
κ_{V_ν} (nepers per cm of H_2O)	.02503	.04239	.06032	.06867	.07099	.02562
$\sigma(\kappa_{V_\nu})$ (nepers per cm of H_2O)	.00027	.00033	.00124	.00180	.00190	.00065
(σ/κ) (percent)	1.08	0.78	2.06	2.62	2.68	2.54
B. Weather ship P						
κ_{V_ν} (nepers per cm of H_2O)	.002504	.04280	.06139	.07013	.07259	.02556
$\sigma(\kappa_{V_\nu})$ (nepers per cm of H_2O)	.00034	.00022	.00157	.00241	.00252	.00058
(σ/κ) (percent)	1.35	0.51	2.56	3.44	3.47	2.27

the *estimation* of a number of quantities entering into (3)–(5). A small uncertainty ε_i in any of these parameters p_i contributes to the total uncertainty in V, for example, an amount $(\partial V/\partial p_i)\varepsilon_i$. We examine below the uncertainty in each of these factors.

Errors in mean radiating temperature (T_{mr}). The zenith thermal emission depends on the vertical distributions of temperature and composition and, hence, the true T_{mr} cannot be determined unless these distributions are known. However, using climatological and/or surface meteorological measurements to estimate T_{mr}, we have found that, over the frequency interval 15–35 GHz, the standard deviations of this quantity are typically about 3–5 K.

Errors in measurement of brightness temperature. Absolute values of water content are related to the absolute measurement of T_{b_ν}; hence all of the many factors determining the absolute calibration of the instrument will influence the moisture determination. For many of the calculations of section 4, we assume an uncertainty in brightness temperature measurement of ±0.5 K.

Uncertainties in dry attenuation. For a given location and season, dry attenuation varies about 5% due to changes in temperature and pressure. With knowledge of surface pressure and temperature, some of this variation can be predicted. Another source of uncertainty in dry attenuation is the inaccuracy in calculating the dry absorption coefficients as a function of temperature and pressure. Our calculations agree to within about 10% with measurements at 6 GHz by *Hogg and Semplak* [1961] and with those of *Altshuler et al.* [1968] at 15 GHz.

Errors in water vapor attenuation coefficients. As in the case of dry absorption, errors in effective water mass attenuation coefficient arise in two fundamentally different ways: first, through uncertainties in molecular constants, spectral line shape, etc.; and second, through variations in the vertical absorption profile that cannot be predicted climatologically.

To determine typical ranges of variation of κ_{V_ν}, means and standard deviation of the quantity were calculated from a data base of radiosonde soundings from two weather ships taken during the years 1967–1968. The climatological variation of each of these stations, ship D in the North Atlantic (44°N, 41°W) and ship P in the Gulf of Alaska (50°N, 145°W), was large. The statistical results are shown in Table 1. For frequencies less than ~31 GHz, the largest climatological variation in water vapor mass absorption coefficient κ_{V_ν} occurs at the resonant frequency $\nu = 22.235$ GHz. Note also the reduced variation at 20.6 GHz.

As discussed by *Waters* [1976], the absorption by molecular water vapor is not completely understood, particularly in the windows between resonant lines. With empirical corrections, the discrepancy between measured and calculated absorption can be reduced to within 10%. Another source of error is the value of the line width constant and its temperature, pressure, and humidity dependence. For example, *Becker and Autler's* [1946] measurements of water vapor absorption lead to a line width constant of water vapor, broadened by one atmosphere of dry air, of 2.78 GHz ($T = 300$ K). *Liebe's* [1969] measurement of the same quantity by dispersion spectroscopy yielded $\Delta\nu_{H_2O-\mathrm{AIR}} = 2.87$ GHz ($T = 300$ K), whereas the value suggested by *Waters* [1976] is 2.96 GHz. Calculations of the water vapor mass absorption coefficient for changes of ±10% in $\Delta\nu$ are shown in Figure 1. The results shown were calculated for the Van Vleck-Weisskopf line shape, using the parameters of *Liebe* [1969], and for the Zhevakin-Naumov-Gross line shape using

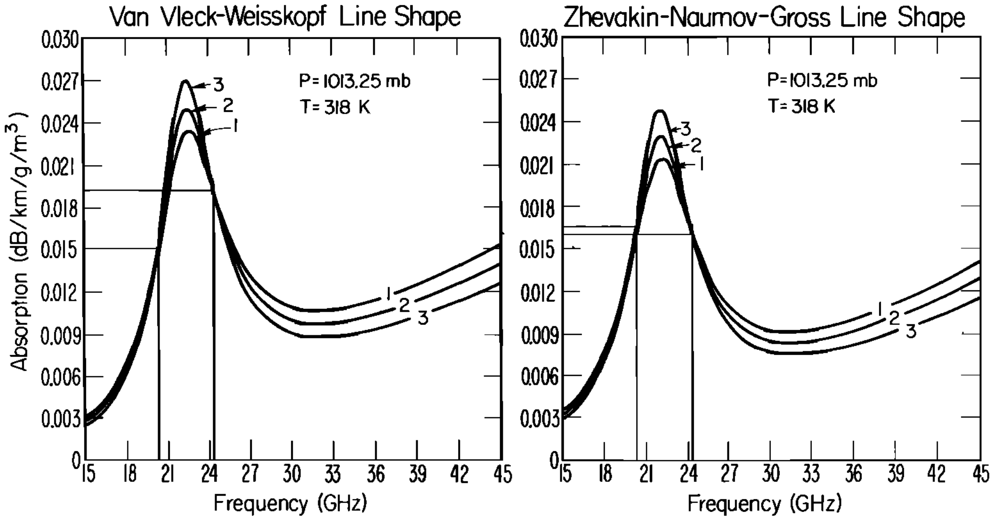

Fig. 1. Calculations of water vapor mass absorption coefficient for ±10% change of line width constant $\Delta\nu_0$. 1 = line width increased by 10%, 2 = original line width, 3 = line width decreased by 10%. For details, see text.

the parameters of *Waters* [1976]. Note that around 20.6 and 24.4 GHz, the absorption changes little for the different line widths. In addition, the differences in absorption for the two line shapes are small at 20.6 GHz. Thus, radiometric observations at the 20.6 GHz frequency could minimize both the effects of uncertainties in the choice of line width parameter and line shape, and the effects due to climatological variation of water vapor and temperature profiles.

Errors in cloud liquid attenuation coefficient. Measurements of the microwave dielectric constant of liquid water show a strong dependence on wavelength and temperature [*Grant et al.,* 1957]. For the wavelengths considered in this paper, and for nonprecipitating conditions, i.e., for maximum particle diameters less than 100 μm, the Rayleigh equation may be used to calculate the absorption from the dielectric constant and the cloud water content [*Mason,* 1971]. Such calculations show that the liquid attenuation changes (decreases) about 2% per °C (increase) in temperature. However, the sensitivity to temperature is somewhat ameliorated for a two-channel system because of the known dependence of the attenuation on frequency and temperature. Without independent information on such cloud parameters as base temperature, base height, or thickness, the uncertainty in average cloud temperature can easily be ±5°C.

For frequencies greater than 15 GHz and during rains that contain an appreciable number of drops whose diameters exceed 1 mm, the Rayleigh approximation is not valid. Furthermore, for the same frequency restriction and for rain rates greater than 1 mm/hr, the scattering contributions to extinction exceed 5%, so that scattering becomes increasingly important in radiative transfer, as either the frequency, or the rain rate, increases. However, *Zavody's* [1974] calculations at 37 GHz indicated that, for rain attenuation less than ~3 dB, the error due to neglecting scattering and estimating the attenuation directly from emission is about 20%. As was pointed out in section 2, the dual-frequency vapor determination requires not the separate values of the upper and lower channel liquid attenuation but only their ratio. This ratio, calculated at 22.235 and 30 GHz, for a rain rate of 0.25 mm/hr differed by about 10% from the ratio calculated for Rayleigh particles. Thus, in light rain, although the Rayleigh assumption could result in an error in liquid determination of a factor of 2 or 3, the effect on vapor determination would be much less serious.

4. RESULTS

Proceeding on the assumption that cloud absorption is Rayleigh, and by using the standard statistical rule for the propagation of errors of correlated

TABLE 2. Error standard deviations used in evaluating resultant errors in the determination of water vapor *V* and cloud liquid *L*.

Frequency (GHz)	Vapor absorption coefficient (percent)	Liquid absorption coefficient (percent)	Dry attenuation (percent)	Mean radiating temperature (K)	Brightness temperature (K)
20.6	5.9	16.6	10.4	4.1	0.5
22.235	10.9	16.5	10.4	3.9	0.5
31.65	5.2	15.7	10.4	5.0	0.5

variables, we have combined the error factors discussed in section 3 with the appropriate partial derivatives to yield a resultant error in both *V* and *L*. The results strongly suggest that most, if not all, non-precipitating clouds will not seriously degrade retrievals of water vapor *V*.

In determining suitable frequencies for dual channel remote sensing, we investigated the pairs

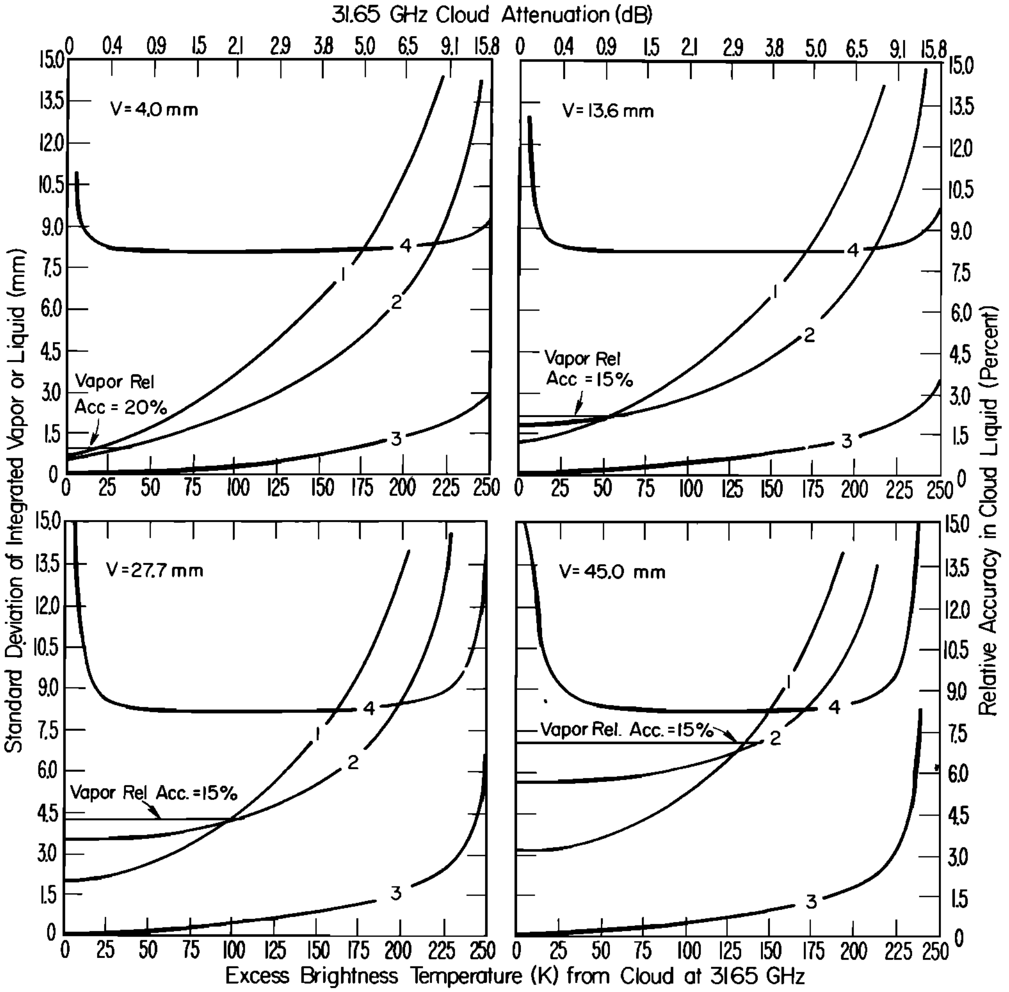

Fig. 2. Errors in the determination of precipitable water as a function of cloud emission. 1 = vapor determination with (20.6, 31.65 GHz) system, 2 = vapor determination with (22.235, 31.65 GHz) system, 3 = liquid determination with (22.235, 31.65 GHz) system, 4 = relative accuracy in liquid with (22.235, 31.65 GHz) system. Error factors of Table 1 are assumed.

(20.6, 31.65) and (22.235, 31.65) GHz. The (22.235, 31.65) pair is already in an operational sounder [*Staelin et al.*, 1975]; the (20.6, 31.65) pair uses a channel, 20.6, at which the error in vapor attenuation coefficient is small. For these frequencies, the error factors in Table 2 were used to evaluate the resultant errors in V and L. The climatological variation of the factors was derived from two years of radiosonde data obtained at weather ship D. The total uncertainties in water vapor and dry absorption coefficients were determined by adding the variance from errors in molecular constants to the climatological variance. We used least-squares parameter fitting to the data of *Becker and Autler* [1946], assuming the Van Vleck-Weisskopf line shape, to estimate the uncertainty in calculating water vapor attenuation, given that temperature, pressure, and humidity are known. Our fit resulted in an rms percentage residual of about 7%, which is more than double the precision of the Becker-Autler data. We are currently investigating this enigma.

Typical results on overall accuracy of vapor and liquid retrievals, for values of average moisture ranging from 4 to 45 mm, and cloud attenuations up to 15 dB, are shown in Figure 2 (in this and subsequent figures, relative accuracy means standard deviation divided by true value). The reader is cautioned, however, that most attenuations greater than 3 dB are caused by rain; therefore, the portions of the curves beyond this value will not

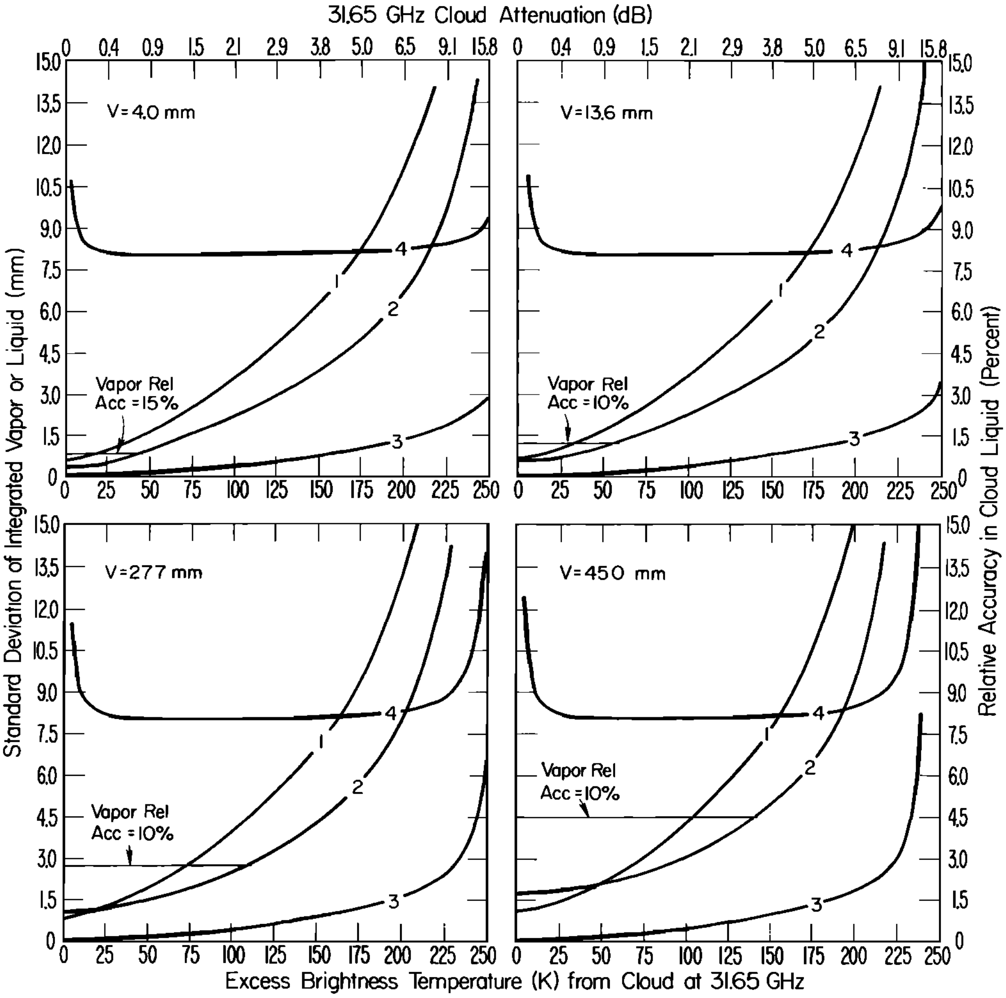

Fig. 3. Errors in the determination of precipitable water as a function of cloud emission. Same notation as in Figure 2. Molecular constants and absorption equations are assumed to be correct.

apply in all cases. Several features are evident from this figure: (1) For clear skies, the 20.6 GHz frequency yields a better accuracy in V than the 22.235 GHz frequency; for $V > 10$ mm, this accuracy generally is better than ~15%. (2) At some cloud density the accuracy for determining V at 22.235 GHz will exceed that of the lower channel. (3) Except for the extremes of the cloud error curves, the accuracy of the derived amount of cloud liquid is quite insensitive to the amount of water vapor present. To estimate system reliability from these curves, it is necessary to know the percentage of time that cloud attenuation levels (or excess brightness temperature levels) are exceeded. *Lo et al.* [1975] reported attenuation at 35 GHz for various types of nonprecipitating clouds. Even up to pre-rain clouds, the largest observed liquid attenuation was 2.3 dB. In addition, some long-term statistics are available. For example, at Holmdel, New Jersey, *Wilson* [1969] determined that the excess attenuation at 30 GHz exceeded 3 dB about 1% of the time (for nighttime zenith observations), and it exceeded 3 dB 2% of the time for daytime solar tracking. Our extrapolation to 30 GHz of *Bergmann and Mullers'* [1976] observations of sky brightness at 13 and 18 GHz, taken at Longmont, Colorado, implies that 3 dB would be exceeded only about 0.1% to 0.2% of the time. Thus, for many locations at least, these rather conservative attenuation estimates along with the accuracies indicated in Figure 2 suggest a high degree of system reliability.

A large component of the total error in water vapor mass absorption coefficient κ_{V_ν} and in dry absorption τ_{d_ν} is the error due to uncertainties in molecular absorption equations. If theoretical and experimental developments would lead to substantial improvement of these calculations, then a large improvement would be obtained in the accuracy of deriving water vapor V during clear and moderately cloudy skies. To show this, we repeated our calculations with conditions identical to those of Table 2, except that uncertainties in path-averaged gaseous absorption were from profile variation only, molecular absorption equations being assumed exact. At the frequencies 20.6, 22.235, and 31.65 GHz, these remaining errors in κ_{V_ν} were 0.8%, 3.2%, and 2.6%, and those in τ_{d_ν} were 2.7%, 2.7%, and 2.7%. The results are shown in Figure 3. Note that the two water channels yield roughly the same accuracy for clear conditions, with the 22.235 GHz channel exhibiting a clear superiority during cloudy conditions. As is evident by comparison with Figure 2, a large reduction in error in V occurs when the molecular component of absorption error is eliminated.

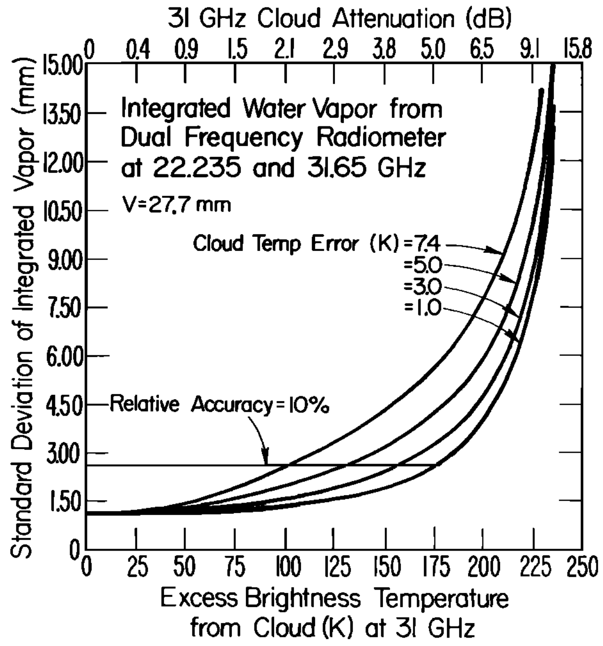

Fig. 4. Errors in the determination of precipitable water for different uncertainties in cloud temperature.

An important factor in correcting V for clouds whose 31 GHz attenuation is greater than ~1 dB is the average cloud temperature. Curves of Figure 4, calculated assuming no error in molecular constants, show this accuracy for various standard deviations of cloud temperature δT_c. Thus, for example, a standard deviation of 1.5 mm in V could arise from a cloud whose attenuation is 0.9 dB and whose temperature uncertainty is 7.4 K or from one whose attenuation is 2.5 dB but whose δT_c is 1 K. Similar calculations investigating the sensitivity to noise levels in the measurement system indicate that the accuracy in V does not degrade seriously until the brightness temperature error exceeds 1 K.

5. DISCUSSION

Calculations indicate that, for 31 GHz cloud attenuation less than 3 dB, a dual frequency ground-based radiometric system can provide useful measurements (usually within 15%) of integrated water vapor and cloud liquid water. These calculations, coupled with available attenuation statistics, imply that such a system could operate 98%–99% of the time for many locations.

The clear-air accuracy of such a system is currently limited by uncertainties in calculation of water vapor absorption as a function of temperature, pressure, and water vapor concentration. To minimize these uncertainties, we are designing a channel at 20.6 GHz, a frequency at which uncertainties in absorption due to uncertainties in line width constants are small. If, however, the uncertainties in knowledge of absorption were eliminated, the 22.235 GHz channel would be an equally good frequency for clear-air probing, and a much better one for separating cloud from vapor.

As was shown in section 4, the cloud effects could be considerably reduced if the effective radiating temperature of the clouds were known. This temperature could be much more accurately estimated if the base height (or base temperature) and thickness were independently measured. Base heights can be measured by a ceilometer, base temperature perhaps by joint infrared-microwave radiometry, and both height and thickness by radar.

The Wave Propagation Laboratory, National Oceanic and Atmospheric Administration, has recently constructed a dual-channel system at 20.6 and 31.65 GHz. After initial performance tests are completed, the system will be operated at Stapleton International Airport, Denver, Colorado, for about six months in 1978. Later, the system will be taken to a more humid location for further tests and evaluation.

A complementary experiment that will independently measure cloud attenuation is also being designed by the Wave Propagation Laboratory (J. B. Snider, personal communication, 1977). The COMSTAR synchronous satellites have a continuously operating beacon at 28.5 GHz. Power levels of this extremely narrow bandwidth beacon will be monitored at the ground by a stable receiver. This measurement, coupled with simultaneous measurements of emission in the same direction and at a closely separated but nonoverlapping frequency band, will provide estimates of both cloud radiating temperature and cloud attenuation. Accuracy estimates of J. B. Snider (personal communication, 1977) suggest that this system can measure attenuation to within ±0.25 dB for attenuation less than 5 dB, and to within ±10% for attenuation between 5 and 10 dB. The accuracy of the mean radiating temperature determination is not high, being about 2.5% at an attenuation of 3 dB. If a dual-frequency system, say 20.6 and 31.65 GHz, were also pointing in the satellite direction, then the estimate of cloud attenuation could receive independent confirmation. The effects of rain on the dual system can also be studied with this experiment.

Acknowledgments. The author expresses appreciation to D. Hogg for many valuable discussions and suggestions during the course of this work, and in addition, to F. O. Guiraud, who performed many of the calculations using climatological data. Finally, the useful suggestions by an anonymous reviewer are acknowledged.

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