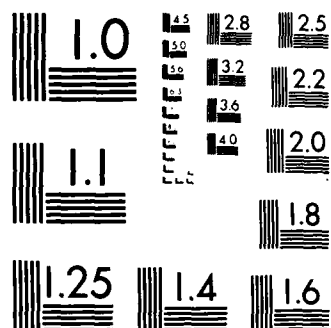


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A Method for Remote Sensing of Precipitable
Water Vapor and Liquid in the Atmosphere
Using a 22-GHz Radiometer

F. I. SHIMABUKURO
Electronics Research Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, CA 90245-4691

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Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
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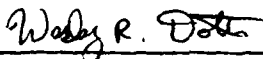
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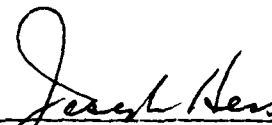
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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.



WESLEY R. DOTTS, Lt, USAF
MOIE Project Officer
SD/CWHB



JOSEPH HESS, GM-15
Director, AFSTC West Coast Office
AFSTC/WCO OL-AB

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A well-known method for retrieving the precipitable water vapor (V) and liquid (L) in a non-precipitating atmosphere utilizes a dual-channel radiometer operating at 20.6 and 31.6 GHz. Statistical retrieval algorithms are used for the determination of V and L. In this study a somewhat different method for retrieval of the quantities V and L, using a radiometer, is described. The atmospheric opacities are determined at three frequencies, (v_1, v_2, v_3) near the water vapor line, from emission measurements. The frequency v_2 is the line		

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19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

center, and the frequencies ν_1 and ν_3 are chosen such that $\nu_2 = \frac{1}{2}(\nu_1 + \nu_3)$. From these three measurements, a differential opacity which is dependent only on the resonant part of the water vapor absorption is derived. From this quantity, estimates of V and the clear atmosphere attenuation are obtained. The cloud opacity is obtained by subtracting the clear atmosphere attenuation from the total attenuation. In light rain the quantity V can be retrieved using this technique.

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CONTENTS

1. INTRODUCTION.....	3
2. PRINCIPLES OF OPERATION.....	5
3. SAMPLE APPLICATION.....	9
4. RESULTS AND CONCLUSIONS.....	15
REFERENCES.....	17

FIGURES

1. Relation Between Precipitable Water Vapor and the Derived Differential Opacity Where the Numbers Indicate the Atmospheric Models.....	11
2. Relation Between the Clear Atmosphere Opacity and Precipitable Water Vapor for the Indicated Atmospheric Models.....	12
3. The Water Vapor Density Distribution up to 6 km for the Indicated Atmospheric Models.....	13



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1. INTRODUCTION

In a series of papers [1]-[6], researchers at the NOAA Wave Propagation Laboratory have described the operation of a dual frequency (20.6 and 31.6 GHz) radiometer and the procedure for retrieving the precipitable water vapor (V) and liquid (L) in a non-precipitating atmosphere using this radiometer. Statistical retrieval algorithms are used for the determination of V and L.

In this paper we describe a method which can give estimates of V and L in a non-precipitating atmosphere, and for V in light rain, from emission measurements using a three-channel radiometer operating near the 22.235 GHz water vapor line.

2. PRINCIPLES OF OPERATION

The attenuation in a non-precipitating atmosphere at the radio wavelengths of interest in this study is attributable to absorption by water vapor, oxygen, and the water droplets in clouds and fog. The absorption coefficients for water vapor and oxygen are found in the literature, e.g., Waters [7] and Liebe [8]. For water vapor,

$$\alpha_w = c_1 \rho v^2 \Delta v_w T^{-3/2} \left[\frac{c_2 e^{-644/T}}{T} f(v, \Delta v_w) + c_3 \right] \text{ km}^{-1} \quad (1)$$

where ρ is the water vapor density in gm^{-3} , v is the frequency in GHz, Δv_w is the linewidth in GHz, $v_0 = 22.235$, T is the temperature in K, and $f(v, \Delta v_w)$ is the Van Vleck-Weisskopf line shape. For the oxygen molecule,

$$\alpha_{\text{ox}} = 1.44 P T^{-3} v \sum_N \left[|u_{N+}|^2 v_{N+} f(v, v_{N+}) + |u_{N-}|^2 v_{N-} f(v, v_{N-}) + \frac{1}{2} |u_{N0}|^2 F(v) \right] e^{-E_N/kT} \text{ km}^{-1} \quad (2)$$

where P is the total pressure in mb, $|u_{N\pm}|^2$ are the matrix elements for the $\Delta J = \pm 1$ transitions, $|u_{N0}|^2$ are the matrix elements for the non-resonant absorption, $v_{N\pm}$ are the resonant frequencies for these transitions, $f(v, v_{N\pm})$ are the corresponding kinetic line shapes, $F(v)$ is the non-resonant line shape, and E_N is the energy for the N^{th} rotational state. The absorption coefficient for oxygen is obtained by summing over all transitions which have contributions at the frequencies of interest. The cloud or fog absorption [9] is given by

$$\alpha_c = 1.885 \frac{M}{\lambda} \text{Im} \left(-\frac{m^2 - 1}{m^2 + 2} \right) \text{ km}^{-1} \quad (3)$$

where M is the liquid water content in gm^{-3} , λ is the wavelength in cm, m is the complex index of refraction of liquid water, and Im means the imaginary part. The index of refraction, m , depends on the temperature and wavelength

such that the cloud absorption coefficient is very nearly proportional to ν^2 [10].

The rain attenuation coefficient is given by

$$\alpha_r = \int Q_t(D) N(D) dD \quad (4)$$

where D is the drop diameter, $Q_t(D)$ is the extinction expressed in terms of the Mie coefficients, and $N(D)$ is the drop size distribution. For a given temperature and rain rate, $\alpha_r \sim \nu^x$. Near the water vapor line, x varies in the range 1.9 - 2.6 for temperatures between 0 and 10 degrees Centigrade and rain rates between 0.25 and 10 mm/hr for the Laws and Parsons [11], and the Marshall and Palmer [12] drop size distributions.

Estimates of the precipitable water vapor and liquid can be obtained by the following procedure. First we assume that at a given elevation angle the total opacity, τ , can be determined by emission measurements. In this study the attenuation direction is assumed to be the zenith. Opacities, τ_1, τ_2, τ_3 , are determined at three frequencies, ν_1, ν_2 , and ν_3 , where ν_2 is the line center of the water vapor line at 22.235 GHz. The frequencies ν_1 and ν_3 are in the vicinity of ν_2 and are chosen such that

$$\nu_2^2 = \frac{1}{2} (\nu_1^2 + \nu_3^2) \quad (5)$$

We show that, for practical purposes, the derived quantity,

$$\tau_d = \tau_2 - \frac{1}{2} (\tau_1 + \tau_3) \quad (6)$$

is dependent only on some integrated function of the water vapor resonant absorption at 22.235 GHz. The utility of the method depends on whether τ_d is a good measure of V .

The opacities τ_1, τ_2 , and τ_3 are estimated from the radiometric formula, given by

$$\tau = \ln \frac{T_m}{T_m - T_e} \quad (7)$$

where T_m is the effective medium temperature, and T_e is the emission temperature of the atmosphere. In practice T_e would be the measured emission temperature, and T_m would be an empirically derived constant, dependent primarily on local meteorological conditions and the characteristics of the antenna system. The quantity T_m would be statistically determined from emission and attenuation measurement on cloudless days using an extra-terrestrial source or by comparing with a previously calibrated instrument. At the same time, τ_d would be derived, and correlated with the precipitable water vapor, V , which would be determined from radiosondes or other calibrated instruments. Also, V would be correlated with the opacities τ_1 , τ_2 , and τ_3 . From these measurements on cloudless days, statistical relations between τ_d and V , and V and τ_0 (clear atmosphere opacity) are obtained. In operation, the cloud opacity is obtained from

$$\tau_c = \tau - \tau_0 \quad (8)$$

and the precipitable liquid is obtained from τ_c using estimates of the cloud temperature.

In the operation given by (6) any opacity with a monotonic behavior in the frequency range ν_1 to ν_3 would tend to cancel (exactly for a ν^0 or ν^2 dependency). In fact, the only kind of function which would not cancel is one with a turning point, such as a resonant absorption; also, because (6) is a differential operation, the error in τ_d is relatively insensitive to errors in T_m , and inferentially, relatively insensitive to the temperature distribution. Near the water vapor line the oxygen absorption coefficient is approximately a linear function of frequency and is sufficiently small, that in (6) for the five model atmospheres to be used as examples, the oxygen opacities are cancelled to a value less than 10^{-4} . Near the water vapor line, for temperatures -10 to +10 degrees Centigrade, the cloud absorption coefficient varies as ν^x where x ranges from 1.88 to 1.95. For a 1 km thick cloud with $M = 1 \text{ gm}^{-3}$ in the above temperature range, the cloud opacities in (6) cancel to

a value less than 10^{-4} . For a 3 km thick rain layer with temperatures in the range 0 to 10°C, and R in the range 0.25 to 10 mm/hr, the rain opacities cancel to a value less than 5×10^{-4} for the two drop size distributions mentioned previously.

3. SAMPLE APPLICATION

The procedure outlined in the previous section will be used to retrieve V and L in five supplemental atmospheres given in the Handbook of Geophysics and Space Environments [13] in a simulated operation. These atmospheric models are the (1) tropical; (2) subtropical, Jul.; (3) subtropical, Jan.; (4) midlatitude, Jul.; and (5) midlatitude, Jan. The top of these atmospheres was assumed to be 21 km, and the relative humidity above 10 km was taken to be the same as that at 10 km given in the Handbook. A 1 km thick cloud layer, with $M = 0.25, 0.50, \text{ and } 1.0 \text{ gm}^{-3}$, with the cloud bottom at 2 or 3 km was superimposed on these models.

Emission temperatures and opacities were calculated for the five atmospheric models at three frequencies, $\nu_1 = 20 \text{ GHz}$, $\nu_2 = 22.235 \text{ GHz}$, and $\nu_3 = 24.265 \text{ GHz}$. The choices of ν_1 and ν_3 are not critical, as long as (5) is satisfied and the frequencies are spaced at a reasonable fraction of a linewidth. These calculations were made with and without cloud cover. The total opacities τ_1, τ_2 and τ_3 were derived from (7) assuming that the calculated emission temperature T_e to be the measured one. In this study we assume the effective medium temperature T_m to be

$$T_m = T_o - 13 \quad (9)$$

where T_o is the surface temperature. In effect this assumes an infinitely narrow antenna beamwidth with 100% antenna beam efficiency. However, these assumptions do not affect the principles of operation and the conclusions reached about the retrieval method. Using the value of T_m in (9), the difference between the derived opacity using (7) and the calculated opacity was less than 0.005 (0.02 dB) for all models, with and without cloud cover.

In retrieving V and the clear atmosphere opacity, linear relations of the form

$$V = a_1 \tau_d \quad (10)$$

and

$$\tau_{01} = b_0 + b_1 V \quad (11)$$

are assumed. The coefficients a_1 , b_0 , and b_1 were determined from the best fit linear regression analysis using the calculated values of τ_1 , τ_2 , τ_3 and V in the five cited model atmospheres without clouds. In practice, T_m , a_1 , b_0 , and b_1 would be statistically determined by correlating emission measurements at a single site on cloudless days with independently measured values of V and τ_0 . In (11) τ_{01} is the estimated clear atmosphere opacity at ν_1 . Any of the other frequencies could have been utilized.

Results are shown in Figs. 1 and 2 for a 1 km thick cloud with $M = 1 \text{ gm}^{-3}$ superimposed on the five atmospheric models. The cloud bottom was at 3 km. Similar results were obtained with the other cloud conditions. The triangles are the calculated values of V and τ_d (Fig. 1), and τ_{01} and V (Fig. 2) for the five numbered cloud-free model atmospheres listed in the beginning of the section. In Fig. 1 the circles give the retrieved values of V using the procedure described earlier. The y-difference between the triangles and circles is the error in the retrieved values of V . The largest error occurs for model 1, which had a water vapor distribution shape that was significantly different from the others. In this model, there was relatively more water vapor lower in the atmosphere. This can be seen in Fig. 3. Because the water vapor line is pressure broadened, τ_d is sensitive to the distribution of the water vapor density. For example, it is seen that if the water vapor is distributed at a higher altitude, less V is required for a given τ_d than for the case where the water vapor is distributed lower in the atmosphere. In Fig. 2 the circles indicate the retrieved value of the cloud-free atmosphere opacity, using the retrieved value of V in (11). The y-difference between the triangles and circles is the error in the estimated cloud opacity for that model.

At frequencies near the water vapor line the attenuation through light rain is primarily absorptive and the effective medium temperature used in the radiometric formula for non-raining conditions can be used to determine the total atmospheric opacity in light rain. Also, as mentioned before, τ_d is a differential quantity and errors in τ_d are relatively insensitive to small errors in T_m . Using this procedure in light rain will give estimates of V .

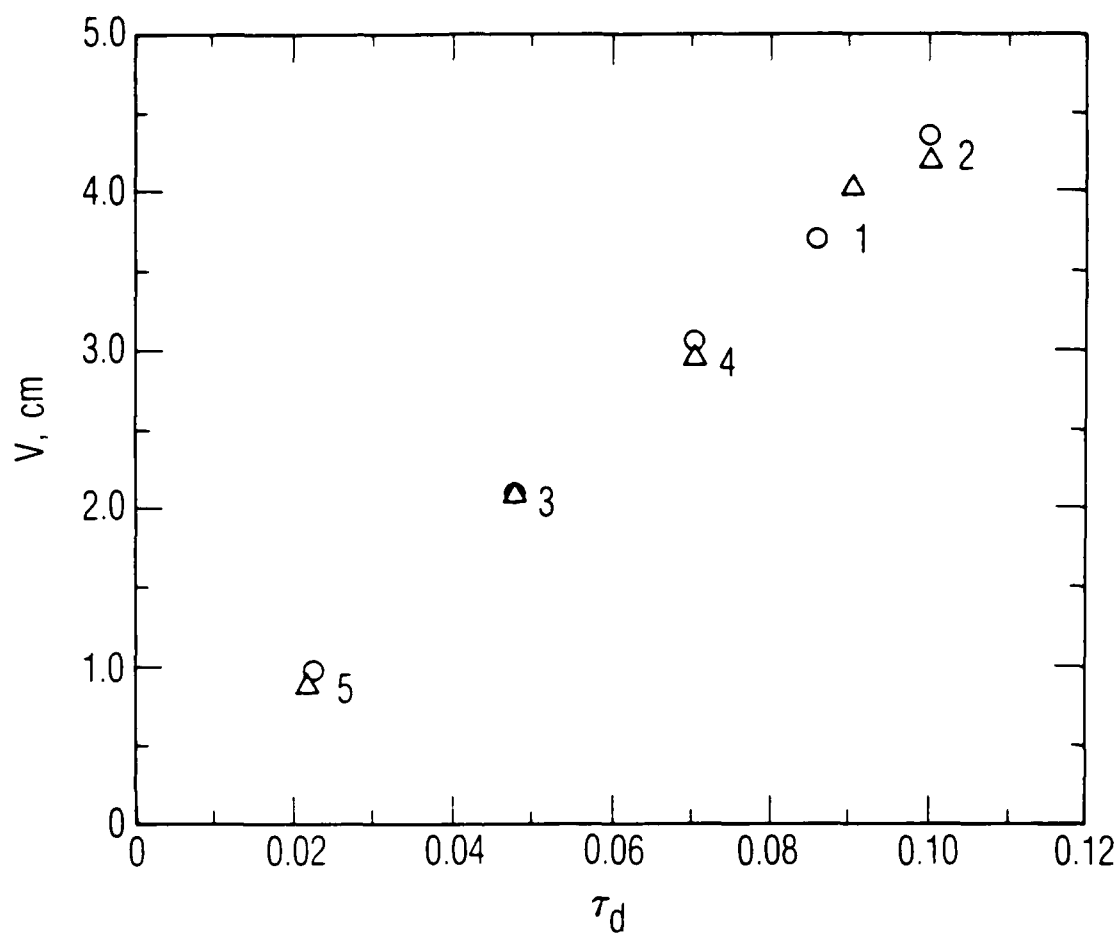


Fig. 1. Relation Between Precipitable Water Vapor and the Derived Differential Opacity where the Numbers Indicate the Atmospheric Models. The triangles are calculated and the circles are the retrieved values

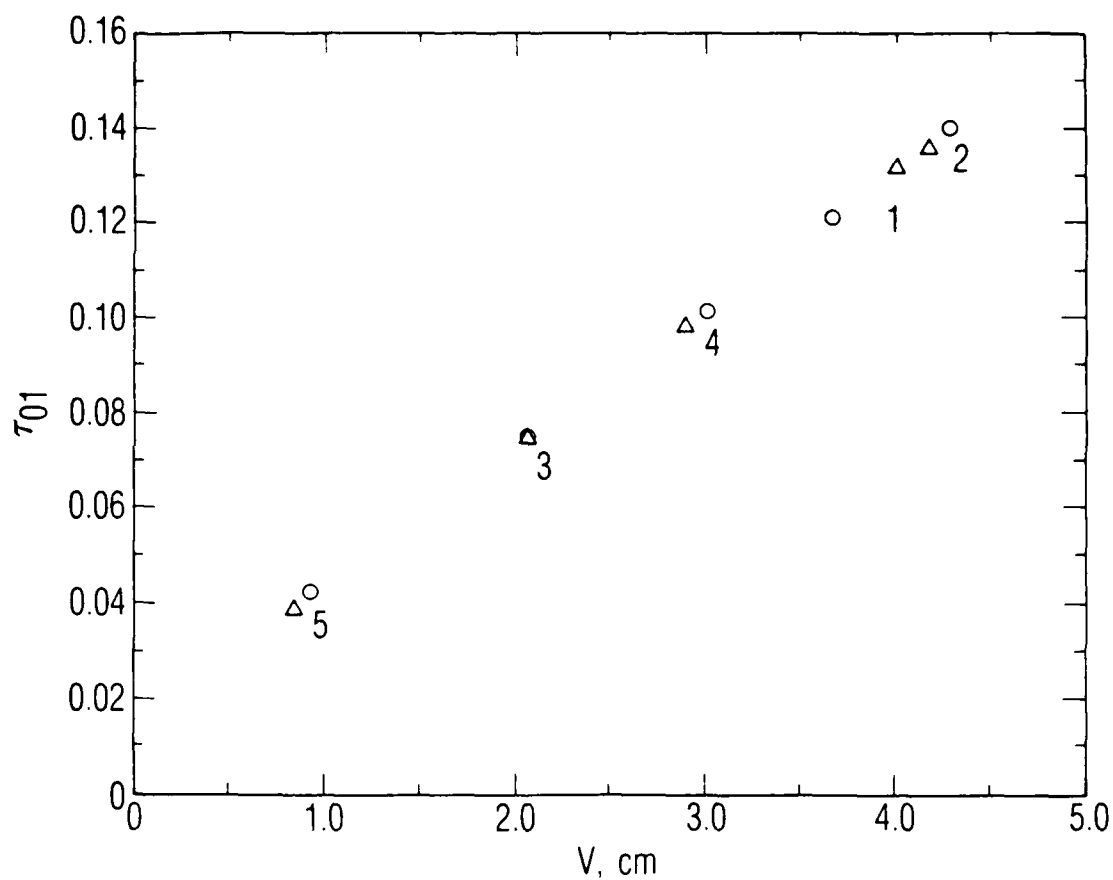


Fig. 2. Relation Between the Clear Atmosphere Opacity and Precipitable Water Vapor for the Indicated Atmospheric Models. The triangles are calculated and the circles are the retrieved values.

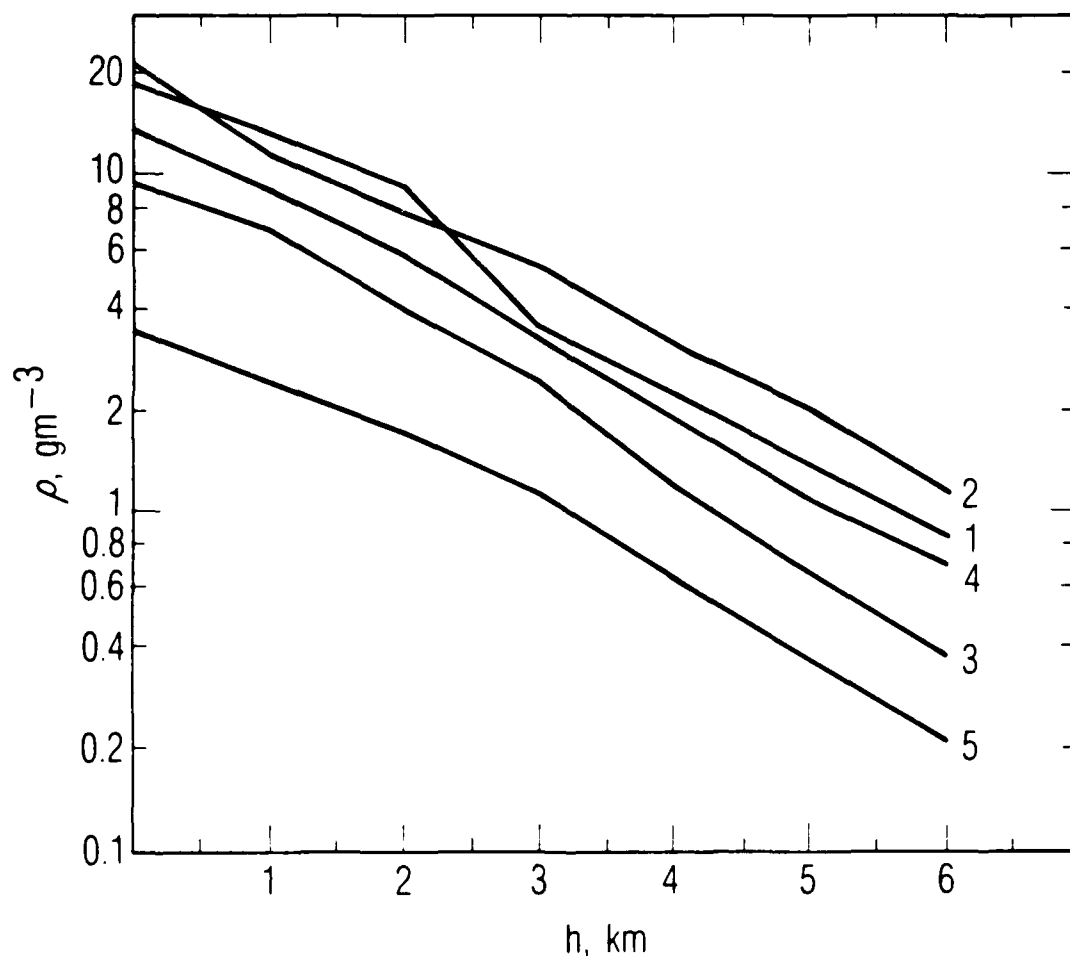


Fig. 3. The Water Vapor Density Distribution up to 6 km for the Indicated Atmospheric Models.

4. RESULTS AND CONCLUSIONS

The accuracy of this method for retrieving V and L depends on the following assumptions: (1) the total opacity can be determined by emission measurements; (2) the differential opacity, τ_d , gives a measure of the precipitable water vapor; and (3) the precipitable water vapor is a measure of the clear atmosphere opacity in non-raining conditions. Assumptions (1) and (3) are essentially utilized in the dual radiometer system operating at 20.6 and 31.6 GHz. It was shown that τ_d is a function only of the water vapor absorption and is sensitive to the height distribution of the water vapor. If, at a given site, the form of the water vapor distribution is highly variable, the rms errors in the retrieved V 's will be correspondingly increased. In this case, instead of a simple τ_d - V relation, more channels can be utilized in the $\nu_1 - \nu_3$ interval and a retrieval algorithm based on a τ_d curve can be implemented. The τ_d curve also gives some information about the water vapor distribution.

It is not possible to give a quantitative assessment of the accuracy of this method for retrieving V and L , in the limited number of illustrated examples. However, the method does have several features which make it attractive for field use. It utilizes a single radiometer and its output is a measured quantity which is a function only of the water vapor density. The system can retrieve V in light rain, and with additional channels, can provide information about the water vapor distribution.

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