Inference of Cloud Temperature and Thickness by Microwave Radiometry from Space[1]

P. C. PANDEY,[2] E. G. NJOKU AND J. W. WATERS

Earth and Space Sciences Division, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

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ABSTRACT

The Scanning Multichannel Microwave Radiometer (SMMR) on the Seasat and Nimbus-7 satellites measured microwave radiation at 6.6, 10.69, 18.0, 21.0 and 37.0 GHz with both horizontal and vertical polarizations. Numerical simulations have been performed to explore the potential of using the 18.0, 21.0 and 37.0 GHz SMMR channels with simultaneous infrared measurements of cloud top height for retrieving cloud temperature differential and thickness over the ocean. The results suggest it is possible to infer cloud vertical thickness to ~0.4 km rms accuracy and cloud temperature differential to ~3°C rms. These accuracies are approximately half the *a priori* variances.

1. Introduction

Clouds are important in the energy balance and dynamics of the atmosphere. Cloud vertical and horizontal extent are needed, for example, in general circulation models, radiation models, and radiative-convective models. Information about cloud extent can also increase our understanding of precipitation.

Recently, Smith and Platt (1978), Wielicki and Coakley (1981) and Chahine (1982) have demonstrated that cloud top heights and fractional coverage can be estimated under a wide variety of atmospheric conditions using infrared measurements. However, it appears that the temperature inside the cloud and its thickness cannot be determined directly using those techniques, because of the opacity of clouds in the infrared.

Microwave radiometry from space has previously been used for cloud liquid water determination, for example by Staelin *et al.* (1976) and Grody (1976). Microwave characteristics of cloud and rain layers in the atmosphere have been investigated by Tsang *et al.* (1977). A recent review by Njoku (1982) describes the general capabilities of microwave radiometers for remote sensing of meteorological and oceanographic parameters from space. We are aware of no previous attempt, however, to estimate cloud temperature and cloud geometrical thickness by microwave measurements from space, which is the subject of this paper.

The technique is based on the fact that microwave emission by clouds depends on the cloud liquid water content, cloud temperature, and microwave frequency. A cloud of given thickness and liquid water content, when moved upward or downward through the atmosphere, has different emission due to the vertical structure of the atmospheric temperature profile. On the other hand, if cloud thickness is changed, emission changes both due to the change in its liquid water content and due to temperature difference of the increased thickness. Thus multifrequency radiometric measurements can, in principle, be used to infer cloud temperature and thickness.

2. Relationship between brightness temperature and cloud parameters

Molecular oxygen, water vapor, cloud liquid water, and rain (if present) are the important atmospheric constituents affecting the microwave brightness temperature. The microwave properties of molecular oxygen and water vapor are described by Waters (1976). The microwave absorption coefficient of liquid water clouds with droplets small compared to a wavelength is (Paris, 1971)

$$\alpha_\nu(\text{cloud}) = 0.0629\left[\frac{3\epsilon_2}{(2+\epsilon_1)^2+\epsilon_2^2}\right]M\nu, \qquad (1)$$

where ϵ_1 and ϵ_2 are the real and imaginary parts respectively of the dielectric constant of water, M is the density of liquid water in g/m^3, and ν is frequency in GHz. The real and imaginary parts of the dielectric constants of water are functions (Lane and Saxton, 1952) of relaxation time, static dielectric constant, and conductivity, which are temperature dependent. Fig.

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[2] NRC-NASA Senior Resident Research Associate. Present affiliation: Space Applications Center, Ahmedabad-380053, India.

1 shows the absorption coefficient of a cloud with $M = 1$ g m^{-3} at different temperatures, computed from (1) with ϵ_1 and ϵ_2 taken from (Hollinger, 1973).

For our simulations described below, calculations of brightness temperature viewing the ocean from space were performed using the radiative transfer equation for a nonscattering atmosphere in local thermodynamic equilibrium given by

$$T_B(\nu) = T_u(\nu) + \tau_\nu(0, h)[\epsilon(\nu)T_s + (1 - \epsilon(\nu))T_d(\nu) + (1 - \epsilon(\nu))\tau_\nu(\infty, 0)T_c], \quad (2)$$

where

$$T_u(\nu) = \int_0^h T(z)\frac{\partial \tau_\nu(z, h)}{\partial z}dz, \quad (3)$$

$$T_d(\nu) = \int_\infty^0 T(z)\frac{\partial \tau_\nu(0, z)}{\partial z}dz, \quad (4)$$

$$\tau_\nu(z_1, z_2) = \exp\left[-\int_{z_1}^{z_2} \alpha_\nu(z)dz\right], \quad (5)$$

where T_u and T_d are, respectively, the upward and the downward radiating brightness temperature contributions due to the atmosphere, T_s is the surface temperature, T_c is the cosmic background brightness temperature, and ϵ is the surface emissivity. The upward and the downward brightness temperature components are integrals of the atmospheric temperature profile $T(z)$ weighted by the vertical derivative of the transmittance function $\tau_\nu(z_1, z_2)$. The limits of integration are from the surface to satellite altitude h. The transmittance function is expressed in terms of α_ν, the atmospheric absorption coefficient. Equation (2) assumes specular reflection at the ocean surface. The equation was numerically evaluated by dividing the atmosphere into layers, each with a specified temperature, pressure, and humidity, which were obtained from radiosonde measurements. Cloud layers were inserted at various altitudes by specifying cloud top, cloud bottom, and liquid water density according to simulated cloud statistics. Within cloud layers water vapor was added to the profiles to increase the relative humidity to 100%. The atmospheric statistics adopted for simulations using Eq. (2) are described in the next section.

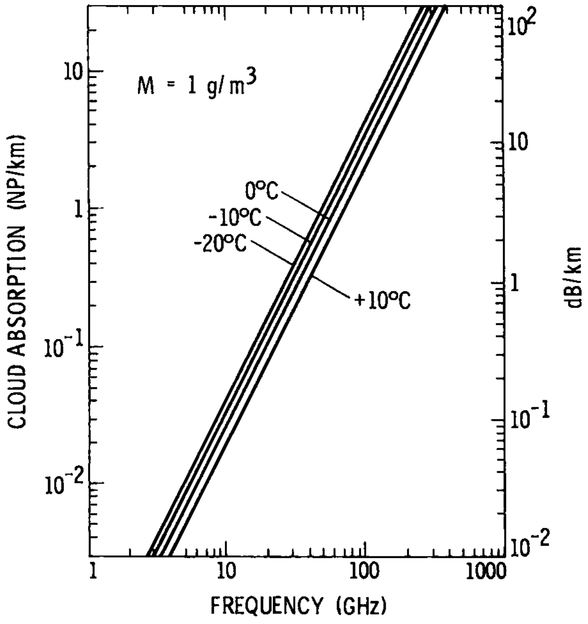

FIG. 1. Microwave absorption by water clouds from 1 to 1000 GHz assuming droplets small compared to the wavelength.

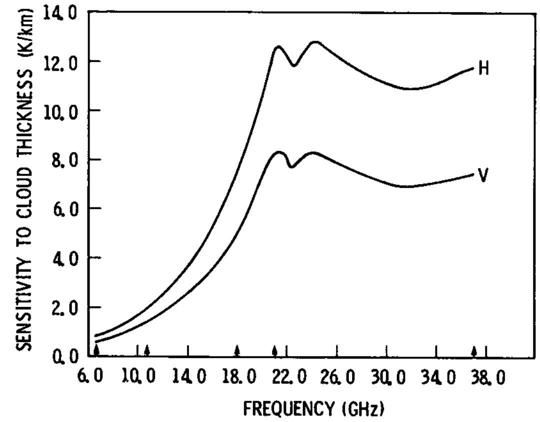

FIG. 2. Sensitivity spectra of horizontal (H) and vertical (V) microwave brightness temperature to cloud thickness. The arrows on the x-axis indicate SMMR frequencies.

Figure 2 shows cloud thickness sensitivity spectra, dT_B/d(thickness), of microwave brightness temperature as observed from space over oceans. These spectra were generated using an annual tropical atmosphere, sea surface temperature of 290 K, wind speed of 15 m s^{-1}, water vapor of 3.0 g cm^{-2}, and liquid water density of 0.1 g m^{-3}. The sensitivity curves were obtained by varying the cloud base from 2.0 to 3.0 km, keeping the cloud top at a constant height of 5.0 km. The dip in the sensitivity curve at 22.25 GHz is due to high attenuation by the water vapor spectral line at that frequency. (Wind speed and surface temperature were kept constant since these affect surface emissivity and hence brightness temperature.)

TABLE 1. Radiosonde statistics used in the numerical experiment. The radiosonde observations were taken between 1968 and 1972. Cloud statistics used in the experiment are given in Tables 2 and 3.

Zone	Region	Latitude	Number of soundings
1	Polar	60°–90° (N and S)	150
2	Midlatitude	30°–60° (N and S)	150
3	Tropical	30°S–30°N	150

TABLE 2. Properties of standard cloud models used in the simulation study (after Gaut and Reifenstein, 1971).

Number	Name	Base (m)	Top (m)	Liquid water density (g m^{-3})
1	Cirrostratus, arctic	4000	6000	0.10
2	Cirrostratus, midlatitude	5000	7000	0.10
3	Cirrostratus, tropical	6000	8000	0.10
4	Altocumulus	2400	2900	0.15
5	Altostratus	2400	2900	0.15
6	Low-lying stratus	150	650	0.25
7	Low-lying stratus	500	1000	0.25
8	Stratocumulus	330	660	0.25
9	Stratocumulus	660	1320	0.25
10	Fair weather cumulus	500	1000	0.50
11	Fair weather cumulus	1000	1500	1.0
12	Fair weather cumulus	1500	2000	0.5
13	Cumulus congestus	1000	1200	0.3
14	Cumulus congestus	1200	1600	0.50
15	Cumulus congestus	1600	2000	0.80
16	Cumulus congestus	2000	2500	1.0
17	Cumulus congestus	2500	3000	0.5

3. Retrieval technique and results

The retrieval technique presented here is a regression approach, which has been used by a number of investigators (e.g., Waters *et al.* 1975; Wilheit and Chang, 1980) to retrieve geophysical parameters from microwave data. We took 450 radiosonde profiles covering all seasons and both hemispheres as our data base (Table 1). The cloud models for our data base are given in Tables 2 and 3. The hypothetical cloud models (Table 3) were added to the cloud models (Table 2) given by Gaut and Reifenstein (1971) to increase the range of cloud parameters. The cloud top height was further varied by a pseudorandom number generator. Table 4 gives the statistics of the data sample used in deriving the regression coefficients. The sea surface temperature and wind speed were varied over the range 270–300 K and 0–15 m s^{-1} and the surface emissivity calculated according to Wilheit (1979).

TABLE 3. List of hypothetical cloud models used with cloud models of Table 2 for simulation study.

Number	Base (m)	Top (m)	Liquid water density (g m^{-3})
1	3000	4000	0.3
2	3500	4700	0.3
3	4000	4800	0.3
4	4500	5200	0.3
5	5300	6400	0.3
6	5800	7500	0.3
7	6000	8000	0.3
8	6200	7200	0.3
9	6000	7000	0.3

TABLE 4. Statistics of the data sample used in deriving the regression coefficients.

Parameter	Mean value	Standard deviation
Cloud temperature differential (°C)	−7.91	5.53
Cloud base (km)	2.96	2.06
Cloud thickness (km)	1.83	0.70
Cloud top (km)	4.79	2.56

This data base was used to calculate an ensemble of brightness temperatures using Eq. (2) as described earlier. Retrieval equations were then obtained by performing a multiple linear regression between cloud parameter and calculated brightness temperatures. The equations have the form

$$p = a_0 + \sum a_j f(T_{Bj}), \tag{6}$$

where p can be either cloud thickness or cloud temperature differential, a_0 is the intercept and a_j are coefficients of the predictor variables, and the subscript j refers to the measurement channel. Nonlinearity of the problem was mitigated by using functions of brightness temperature [$f(T_B) = \ln(280 - T_B)$] for the frequencies 18.0, 21.0, and 37.0 GHz. Previous studies (e.g., Grody *et al.*, 1980) have shown that the integrated water vapor and cloud liquid water amounts are more closely linearly related to these functions than to the brightness temperatures themselves. The other SMMR frequencies, 6.6 and 10.7 GHz, were not used in the retrieval scheme. The calculated brightness temperatures were perturbed by Gaussian noise having standard deviations of 0.45, 0.45 and 0.90 K for the respective frequencies, to simulate the SMMR instrument noise.

The five most sensitive SMMR channels (18V, 18H, 21H, 37V and 37H for cloud temperature differential and 18V, 18H, 21V, 21H and 37V for cloud thickness) and the cloud-top height were used in the prediction equation. (It was found that cloud-top height and cloud-top temperature gave identical performance when used as predictors.) In practice, cloud-top height can be estimated from infrared measurements (Chahine, 1982) with an rms accuracy of ~50 mb which corresponds to about 0.5, 0.7, and 1.5 km height error at low, middle, and high tropospheric levels. A cloud-top height rms error of 0.9 km was assumed in our study. The regression coefficients obtained for cloud temperature differential and thickness are given in Table 5. The cloud temperature differential was computed by multiplying average temperature lapse rate within the cloud with cloud thickness. The cloud was divided into layers (~0.2–0.3 km thick) and the lapse rate of each layer was obtained by dividing the temperature difference of the layer by its thickness. The average lapse rate within the cloud was then obtained from the mean of the lapse rates of the individual layers within the cloud. The coefficient of determination, R_2, which is a measure of goodness of fit (Green and Carrol,

TABLE 5. Regression coefficients for simulated retrieval of cloud temperature differential and cloud thickness from simultaneous cloud top height and SMMR measurements. Predictors are functions of brightness temperatures $f(T_B) = \ln(280 - T_B)$.

Parameter	Intercept	Predictor	Coefficients	Root mean square error	R^2
Cloud temperature differential (°C)	−119.9238	18V	31.3095	3.1	69.26
		18H	−64.7607		
		Cloud top	−1.8383		
		21H	13.8590		
		37V	−36.2355		
		37H	31.2996		
Cloud thickness (km)	−1.3155	18V	−3.2125	0.43	62.65
		18H	3.9367		
		21V	2.4566		
		21H	−2.3741		
		37V	−0.5631		
		Cloud top	0.2245		

1978), and the rms error in estimating these parameters are also given in Table 5. The results indicate that the cloud temperature differential and cloud thickness can be determined to ~3.0°C and ~0.40 km rms accuracies respectively. This is an improvement of approximately 50% over the *a priori* variation in these parameters.

In order to verify the technique with independent data, we generated an independent verification data base using 234 different radiosonde measurements that were different from those used for determining the regression coefficients. Cloud models of Table 2 and 3 were used with a pseudorandom number generator for cloud top heights, which provided slightly higher (±1 km) range of the cloud parameters. Other aspects of the retrieval were the same as described above. The cloud temperature differential and thickness from this data set constitute the "true" parameter values; retrieved values were obtained using the regression equations with coefficients in Table 5. Fig. 3 shows a plot of true versus retrieved cloud temperature differential. An rms error of ~3°C was obtained. Fig. 4 shows the plot of true thickness vs retrieved thicknesses. An rms accuracy of ~0.4 km was obtained. It is seen from the figure that cloud thickness retrieval is degraded for cloud thicknesses larger than ~2.5 km where this quasilinear regression technique underestimates the thickness. Nonlinear, iterative retrieval techniques for

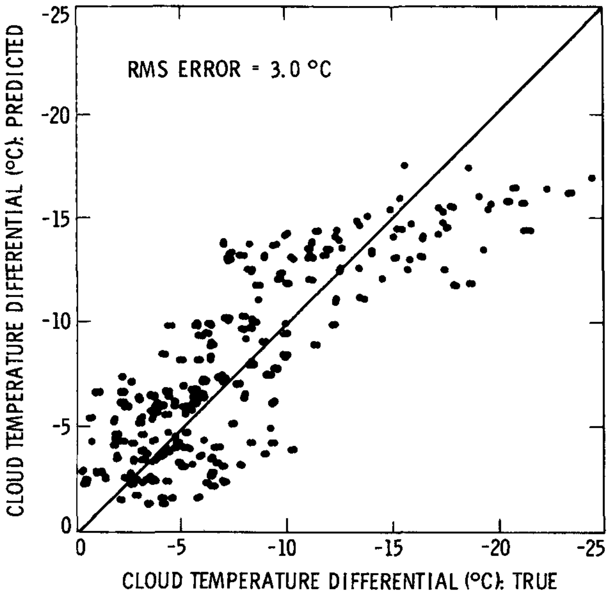

FIG. 3. Comparison of "true" and retrieved cloud temperature differential.

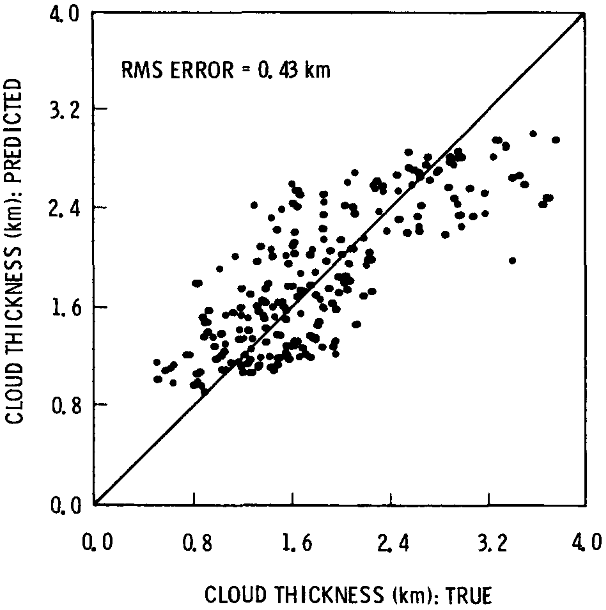

FIG. 4. Comparison of "true" and retrieved cloud thickness.

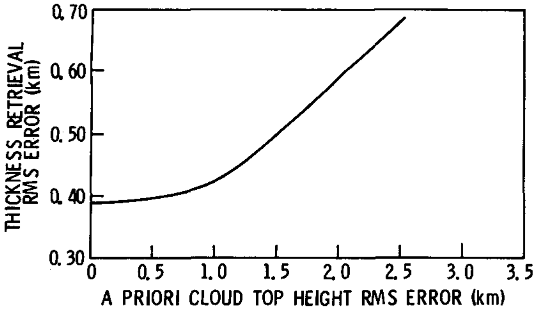

FIG. 5. Variation of rms error in the retrieval of cloud thickness versus assumed rms error in cloud top heights.

predicting these cloud parameters might improve the retrieval accuracy. It should also be mentioned that the retrieval accuracy is degraded if the cloud is isothermal and is improved if the cloud has a high lapse rate. The effect of rms error in cloud top height on the retrieval accuracy for cloud thickness has also been investigated and is shown in Fig. 5. Cloud-top height uncertainties greater than about 1 km increasingly reduce the cloud thickness accuracy.

4. Conclusion and remarks

The results indicate that existing space-borne microwave and infrared radiometers, operating together, can measure cloud thickness and temperature differential to an accuracy of about half the *a priori* variance in these parameters. For our simulations this represents an rms accuracy of ~0.4 km for cloud thickness and ~3°C for temperature differential. Such accuracies may be useful for cloud climatological studies (ICSU, WMO, 1982). It is likely these accuracies can be improved by future experiments that are more nearly optimally designed for this purpose.

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