SCATTERING EFFECTS ON MICROWAVE PASSIVE REMOTE SENSING OF CLOUD PARAMETERS

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1. INTRODUCTION

As an important tool of atmospheric remote sensing, microwave radiometers are used for temperature profiling, and vapor and liquid column measurements (Hogg et al. 1983; Solheim et al.1998). Radiometer measurements are inexpensive compared to the cost of radar, and it can provide all-time observation in both cloudy and clear air situations. However, using radiometer measurements can be more difficult than a radar measurement because: (1) the measured brightness temperature is proportional to cumulative emission from various layers; (11) both scattering and absorption contribute to the measured radiation, which is governed by an integral-differential Radiative Transfer (RT) equation; (iii) the relation between brightness temperature and the atmospheric parameters is non-linear. Therefore, linear and log-linear models have limited applicability.

The atmospheric particles (liquid water droplets and ice crystals) emit, absorb and scatter at microwave frequencies. The absorption is directly related to emission. The scattering affects radiation measurements indirectly through scattering of the radiation emitted by atmospheric particles. The dependence of the measured radiation on the scattering and absorption is governed by the RT equation.

There are a number of mathematical methods for solving the RT equation. For temperature profiling, the absorption approach is usually used, and the scattering effect is ignored as in Solheim et al. (1998). The absorption approximation gives reasonable results when the single scattering albedo of the medium is low and the optical depth is small. Recent studies show that the scattering effect of cloud particles can be important (Wang et al. 1998). In the case of significant single scattering albedo, rigorous methods should be used for solving the RT equation. Scattering radiation is comparable to absorption at a higher frequency and is described by phase function. Mie scattering is used for computing phase function and extinction coefficient.

In this paper, we study the scattering effects on the brightness temperature and the retrieval of atmospheric parameters. First, we discuss the parametric radiative transfer model for the atmosphere containing liquid and ice particles. Then, the RT equation is solved using three different approaches; namely absorption, extinction and full solution. The results of three approaches are compared. We use the full solution of the RT equation to simulate atmospheric radiation and calculate the brightness temperature at 20.65, 31.65, 90, 150, and 220 GHz. Lastly, the simulated brightness temperatures are then used for training the neural network and the atmospheric parameters are retrieved using the neural network.

2. EFFECT OF SCATTERING ON RADIOMETER MEASUREMENTS

2.1. Atmospheric Model

The atmosphere contains gaseous molecules (oxygen and water vapor), liquid and ice cloud particles. Microwave radiation from the atmosphere is due to the absorption and scattering of gaseous molecules and cloud particles. To simulate the atmospheric radiation and retrieve the parameters using radiometric measurement, a simplified atmospheric model is needed. Particularly, temperature and vapor profiles can be parameterized using linear and exponential functions.

Air temperature decreases smoothly with height. The temperature profile can be approximated by a linear relationship as

$$T(z) - T_A - \Gamma z \quad (1)$$

where T_A is the effective temperature at the surface and Γ is lapse rate. It should be noted that T_A and Γ

are effective variables and are not necessarily equal to the actual near surface temperature and mean lapse rate, respectively.

Water vapor density profile is approximated by exponential function,

$$\rho v(z) = \frac{V}{H_v} \exp\left(-\frac{z}{H_v}\right) \qquad (2)$$

where V is integrated water vapor content and H_v is water vapor scale height.

We assume that clouds are homogeneous layers containing liquid, ice, or mixed phase. Cloud droplet size distribution is an important quantity in determining cloud micro-physics and atmospheric radiation. The atmospheric particle size distribution is assumed to be modified Gamma distribution as,

$$n(r) = ar^{\alpha} \exp(-br^{\Upsilon}) \qquad (3)$$

where r is the radius of particles, α and Υ are shape parameters, α is related to the water content (WC) and b is related to the particle mode size as follows:

$$b = \frac{\alpha}{\Upsilon^{r_c^{\Upsilon}}} \qquad (4)$$

$$\alpha = \frac{3\Upsilon b^{(\alpha+4)}/\Upsilon}{4\pi\rho\Gamma((\alpha+4)/\Upsilon)} WC \qquad (5)$$

where WC is LWC (liquid water content) for liquid cloud and IWC (ice water content) for ice cloud, and ρ is the appropriate density of liquid or ice phase. $\Gamma(...)$ is the gamma function, not the lapse rate.

2.2. Comparison between Absorption, Extinction, and Rigorous Approaches

Atmospheric radiation is due to the emission (absorption), scattering, and extinction of cloud particles. The radiative transfer process (RT equation) describes the interaction between emission and scattering. The RT equation can be solved using three different approaches: absorption, extinction, and full solution.

Absorption approach: In the absorption approach, scattering term is neglected. In this case, extinction is approximated by the absorption. This is valid for a gaseous medium or cloud composed of small particles ($ka \ll 1$) in which the Rayleigh scattering approximation is valid. The absorption approach is primarily applicable to the temperature and vapor profiling using emission from oxygen and water vapor respectively (Solheirn et al. 1998; Westwater et al. 1980).

Extinction approach: In the extinction approach, the emission coefficient is assumed to be the extinction coefficient; i.e., the sum of both absorption and scattering coefficients which are calculated using the Mie scattering theorem. The extinction approach is a better approximation when the medium is optically thick, highly scattering and almost isotropic. In this case, the scattering effect is similar to emitted radiation except that the emission coefficient describes both emission and scattering processes. This is used for retrieving rain attenuation and liquid water content (Westwater et al. 1980; Zhang et al. 1985).

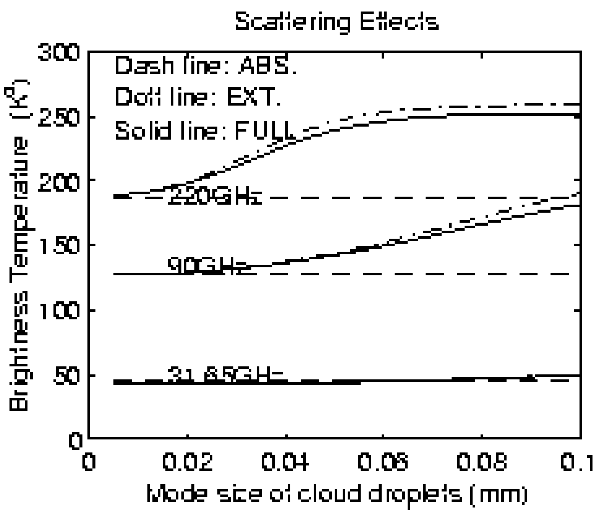
Full solution: The full solution solves RT equation with emission and scattering using numerical methods such as the invariant embedding method (Evans, 1990).

For liquid cloud, it is usually assumed that absorption dominates over scattering. The Rayleigh approximation is applicable for computing the absorption coefficients of cloud droplets and the absorption approach is used for calculating the atmospheric radiation or brightness temperature. Recently, however, it has been found that a small number of large cloud droplets can contribute significantly to the scattering even when the mode size of the particle size distribution is in the order of 10 to 100 micrometers. In this case, the Rayleigh scattering approximation is not valid and an exact solution must be used.

We use the above three approaches to calculate the downwelling radiation and show the brightness temperature as a function of mode size in Figure 1. The fixed parameters are surface temperature $T_A = 283^oK$, integrated vapor $V = 0.6cm$, surface pressure $P_o = 84KPa$, liquid water content $LWC = 0.5g/m^3$, cloud base height $3Km$, and cloud thickness of $1Km$. For the modified Gamma distribution of cloud droplets, the shape parameters are $\alpha = 2$ and $\Upsilon = 1$. We see that the three approaches give almost the same brightness temperature at a frequency of 31.65GHz, but they differ at 90 and 220GHz. At 31.65GHz, the brightness temperature does not change much as the droplet size increases. This is because the cloud particles are relatively small and Rayleigh scattering is valid. In this case, the extinction is the same as the absorption, and is proportional to liquid water content. However, at higher microwave frequencies of 90 and 220GHz, the brightness temperatures calculated by the extinction approach and exact solution increase and the differences between the absorption approach and full solution increase as the cloud drop size increases. The results of the extinction approach agree with the full solution better than the result of absorption approach, but the difference can be up to10^{o}K for the mode size larger than 50pm. This is because large droplets are in the Mie scattering region and both absorption and scattering contribute significantly to the radiation.

Figure 1. Comparison Of radiation from liquid cloud calculated using absorption approach, extinction approach, and full solution.

3. SENSITIVITY STUDIES AND RETRIEVAL



Using the full solution, the RT equation is solved and the relations between the radiation and the atmospheric parameters are discussed. The brightness temperature is calculated at four frequencies (20.65, 31.65, 90, and 220GHz) for both liquid and ice cloud. The results are plotted as functions of water content and mode drop size, and shown in 3-D plots (see Figs. 2, and 3). For liquid cloud, as shown in Fig. 2 the brightness temperature linearly increases as liquid water content and has almost no dependence on drop size at 20.65 and 31.65 GHz. However, at the higher frequencies (90 and 220 GHz), The brightness temperature depends on liquid water content non-linearly, and is also sensitive to drop size. That is because the large cloud droplets are in Mie scattering region and the extinction cross section is not linearly proportional to the volume of the cloud droplet as in the Rayleigh scattering.

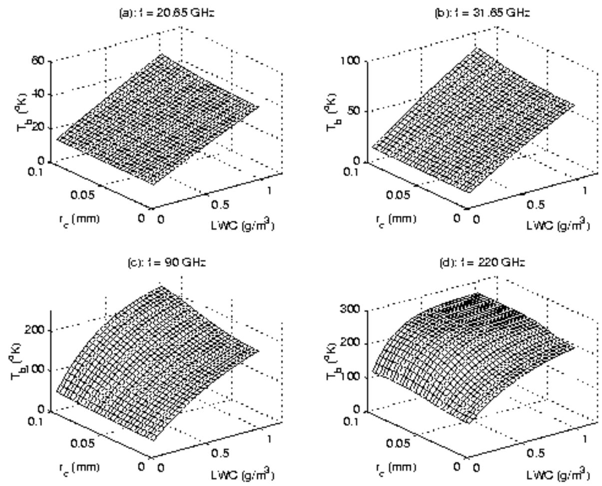


Figure 2. Dependence of brightness temperature on liquid water content and droplet size for liquid cloud. The results are shown for 20.65, 31.65, 90, and 220 GH.z. For a specific LWC, brightness temperature increases as the droplet size increases.

Figure 3 shows the results for ice cloud. The brightness temperature increases as the ice water content and the mode drop size increases at 20.65 and 31.65 GHz. At the higher frequencies 90 and 220 GHz, however, the brightness temperature increases with ice water content, but its dependence on drop size is multi-valued. In the ice cloud, the ice particle size can be of order of wavelength, and extinction depends on both scattering and absorption. At the lower frequencies 20.65 and 31.65, the ice particles are in Rayleigh scattering and the extinction coefficient per unit water content increases as the drop size increases. At higher frequencies, the scattering from ice particles changes from Mie to geometrical optics value and this change causes the decrease in extinction coefficient.

The brightness temperature non-linearly depends on water content and droplet size. Because of the non-linear relationship, it is difficult to retrieve the atmospheric parameters using a simple curve fitting technique. However, neural network techniques have shown advantages in dealing with the non-linear problems and been used in passive remote sensing measurements (Tsang et al. 1992, Li et al. 1997). Here, we apply neural network techniques to the multiparametric retrieval from multi-frequency brightness temperatures based on the radiative transfer model.

We build the neural network-based retrieval model with the parameter space of integrated water vapor *(V)*, water content *(WC)*, cloud base height (H_b), and mode drop size (r_c), and radiation at four frequencies: T_1, T_2, T_3, and T_4. Considering the training speed and memory requirement, we use a radial basis neural network with the brightness temperature $\boldsymbol{X} = (T_1, T_2, T_3, T_4)$ as input, and the atmospheric parameters as output $\boldsymbol{Y} = (V, WC, H_b, r_c)$. Accuracy of neural network is also tested using a different data set than the training data set. For liquid cloud, the brightness temperatures at frequencies 20.65, 90, 150, and 220 GHz are used. The retrieved results are plotted as functions of input parameters and shown in Fig. 4. The solid lines are for self-test, i.e. test and training data sets are the same. The straight line shows the convergence for the self-test case. The dashed lines are the tests for a different data set. The retrieved parameters are close to the input parameters. After 1728 batch training, the normalized output errors are 0.000317 for self-test and 0.0064 for different data set, respectively. For ice cloud, we use brightness temperatures at frequencies 20.65, 31.65, 90 and 150 GHz and show retrieval results in Fig. 5.

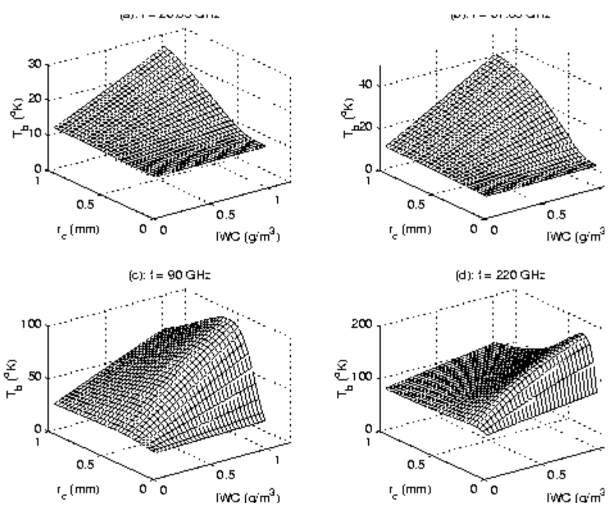


Figure 3. Dependence of brightness temperature on liquid water content and droplet size for ice cloud. At lower frequencies (20.65 and 31.65 GHz), brightness temperature increases as the ice particle size increases. Folding in the plots for higher frequencies (90 and 220 GHz) is due to the transition from Mie to geometrical optics scattering.

4. CONCLUSIONS

In this paper, we compared the three approaches for solving the RT equation. The radiative transfer model is used to retrieve atmospheric parameters such as water content, mode drop size, and cloud base height. The radial basis neural network is used in the retrievals. It is found that the scattering effect can be important at frequencies higher than 100GHz even for liquid cloud, and an exact solution of the RT equation is necessary. The brightness temperature is also sensitive to the mode drop size, which was ignored in earlier parameter retrieval studies. Preliminary results are presented only for single-phase clouds (liquid cloud or ice cloud). We will study mixed phase clouds; i.e., which liquid particles and ice droplets co-exist.

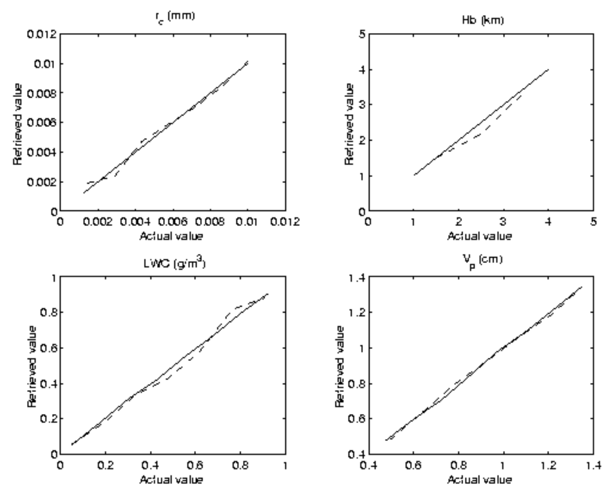


Figure 4. Retrieval of liquid cloud parameters: droplet size (r_c), cloud base height (H_b), liquid water content (LWC), and integrated water vapor (V_p). The solid line is the self-test case. The dashed line is for a different data set from the training data.

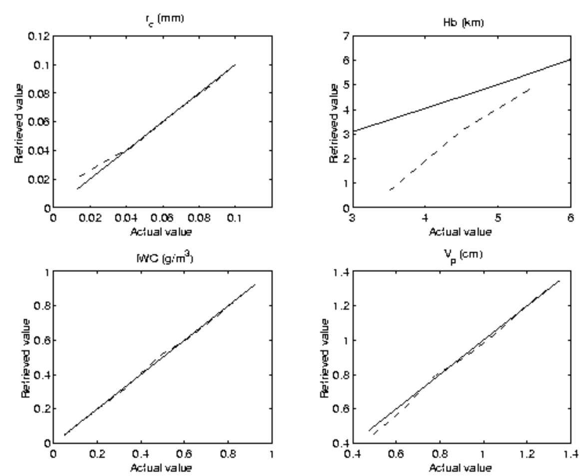


Figure 5. Retrieval of ice cloud parameters: droplet size (r_c), cloud base height (H_b), liquid water content (IWC), and integrated water vapor (V_p). The solid line is the self-test case. The dashed line is for a different data set from the training data.

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