Theory for Microwave Thermal Emission from a Layer of Cloud or Rain

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Abstract—Microwave thermal emission from a layer of cloud or rain consisting of spherical particles has been investigated. Scattering effects are studied in great detail with both numerical and analytical approaches. In the absence of ground emission, it is found that scattering induces brightening for optically thin layers and vice versa for optically thick layers. As a function of observation angle brightening occurs near nadir while darkening occurs at large angles in the case of small optical thickness. For large optical thickness, darkening occurs at all angles because of backscattering effects. When the layer of cloud or rain is above an air layer and an ocean surface at a higher temperature, it is found that the darkening effect at large optical thickness is much more pronounced. The darkening effect is also larger for vertical polarizations because the ocean emits more vertically polarized components. The effect of thermal emission and molecular absorption by atmospheric gases is also taken into account. Results obtained from analytical formulas under single scatteirng assumptions are compared and illustrated.

I. INTRODUCTION

MICROWAVE radiometry has been used for passive remote sensing of the earth and the atmosphere [1]-[3]. The effects of atmospheric liquid water on radiometric measurements are interesting for at least two reasons. Firstly, properties of cloud and rainfall layers such as their water content and drop size distribution may be inferred [4]-[6]. This information is useful for meterological purposes. Secondly, absorption, emission, and scattering of intervening cloud and rainfall layers may have a significant effect on radiometric measurements of the earth surface from aircraft and satellites.

Numerous studies have been made in the past to compute extinction coefficients, attenuation, and scattering properties of atmospheric water droplets by using Mie theory for absorption and scattering with suitable drop size distributions [7]-[11]. Many of these were concerned with active techniques [12]-[15]. For passive remote sensing, studies of microwave thermal emission from cloud and rainfall were carried out by neglecting scattering effects [6]. Under such assumptions the radiative transfer equations give rise to simple integral representations for brightness temperatures. Recently, scattering effects on the brightness temperature in the nadir direction, were taken into account by using a single scattering assumption. More rigorous theories of scattering have been developed for emission from terrestrial subsurfaces [17]-[23].

In this paper, we study the problem of thermal emission from a layer of cloud or rain consisting of spherical scattering particles. From the practical point of view, it is far from a satisfactory model for the actual atmosphere but only represents a positive step towards that direction. From the analytical point of view, the problem already has presented a formidable task that had not been solved before. We shall use complete Mie expressions for the extinction and absorption coefficients, and the scattering phase functions. To accomodate coupling between specific intensities in directions other than nadir, scattering phase functions that are more general than those commonly [10] used have to be developed. Polarization dependence is preserved. We also use drop size distributions to characterize water droplets in cloud and rainfall. The resultant radiative transfer equations are solved by numerical approaches for a layer of cloud or rain in the presence of thermal emission from an ocean surface and thermal emission and molecular absorption by atmospheric gases. Analytical expressions are also obtained from the equivalent integral equations by using two different iteration schemes and compared with the numerical method. Various numerical results are presented to illustrate the dependence of brightness temperatures on frequency, observation angle, and polarization.

II. FORMULATION

Consider a cloud layer consisting of spherical particles with permittivity ϵ_s. The layer consists of distributions of different particle sizes and extends from $z = 0$ to $z = t$. (Fig. 1) The radiative transfer equations inside the cloud take the following form:

$$\cos\theta \frac{d}{dz} I_v(\theta, z) = -(\kappa_{ed} + \kappa_{ag}) I_v(\theta, z) + (\kappa_{ad} + \kappa_{ag}) CT + \int_0^\pi d\theta' \sin\theta' \{(v, v')_d I_v(\theta', z) + (v, h')_d I_h(\theta', z)\} \tag{1a}$$

$$\cos\theta \frac{d}{dz} I_h(\theta, z) = -(\kappa_{ed} + \kappa_{ag}) I_h(\theta, z) + (\kappa_{ad} + \kappa_{ag}) CT + \int_0^\pi d\theta' \sin\theta' \{(h, v')_d I_v(\theta', z) + (h, h')_d I_h(\theta', z)\} \tag{1b}$$

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