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Single scattering from frozen hydrometeors at microwave frequencies

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ABSTRACT

Scattering of electromagnetic waves from homogeneous or coated spheres can be computed in a mathematically exact way using the Mie theory. Therefore, for many approaches in remote sensing, frozen hydrometeors are parameterized as ice spheres. However, many frozen hydrometeors have non-spherical overall shapes and lack a spherically symmetric internal structure. They exist in a huge variety of shapes and exhibit different mixtures of ice, water and air. Therefore it is desirable to accurately compute scattering from non-spherical particles in order to clearly understand the effect the shape of a hydrometeor has on its scattering pattern. In this study, single scattering parameters like scattering cross section, absorption cross section, and asymmetry factor were calculated for frozen hydrometeors using the Discrete Dipole Approximation (DDA). The particles were modeled as hexagonal plates, columns, needles and dendrites by applying known dimensional relationships. The calculations were carried out over a wide range of centimeter and millimeter-wavelengths (1 GHz to 300 GHz), since millimeter-wave radiometers are highly sensitive to scattering by frozen hydrometeors in the atmosphere. The study results show that for size parameters <1 (a ratio between wavelength and particle size) the scattering cross section of randomly orientated ice crystals is close to that of an equal volume ice sphere. Absorption cross section and asymmetry factor of non-spherical particles however are up to twice as high as that of equal volume ice spheres. Further the influence of the assumed model for the refractive index of ice at microwave wavelengths on the scattering parameters is investigated.

1. Introduction

Scattering of microwaves from non-spherical ice particles has been a field of research for more than one decade. One reason lies in the interest of measuring precipitation from space (remote sensing). Also, for climate studies, measuring precipitation on a global scale is essential. Radar networks however, can detect only a small part of the global precipitation. One approach is to detect frozen hydrometeors with radiometers working at millimeter wavelength (e.g. Skofronick-Jackson et al., 2004). This requires a radiative transfer model in which the assumed scattering parameters are of fundamental importance.

Another reason for calculating scattering of microwaves from non-spherical ice particles is the interest of using millimeter wave radars for the remote sensing of clouds. Millimeter wave radars are especially sensitive to cloud ice crystals and water droplets. Ice particles are dominant scatterers in cirrus clouds which play a significant role in the earth's radiation budget. The potential of ground based polarimetric cloud radars was evaluated by Lemke and Quante (1999). For such considerations, the backscattering characteristics of ice crystals are of special interest. Furthermore, the use of passive submillimetre-wave measurements to retrieve cloud ice water content and ice particle size was suggested (Evans and Stephens, 1995). A mission to measure the ice water path from space is CIWSIR (Cloud Ice Water path Submillimetre Imaging Radiometer) (Buehler et al., 2007). The idea is to use a 12-channel radiometer with channels between 183 and 664 GHz.

Mainly two methods are applied to calculate scattering of microwaves from non-spherical ice particles. One method is the discrete dipole approximation (DDA). The DDA – first described by Purcell and Pennypacker (1973) – is a method to

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calculate scattering of arbitrarily shaped particles. The DDA has been used to calculate microwave scattering from ice crystals by Evans and Stephens (1995), Lemke and Quante (1999), Kim (2006) or Hong (2007). Error analyses have been done by Liu and Illingworth (1997) and Lemke et al. (1998). An alternative approach is the Finite Difference Time Domain (FDTD) method. Scattering calculations of ice crystals for 94 and 220 GHz using FDTD have been done by Tang and Aydin (1995), and Aydin and Walsh (1999).

The first aim of this study is to test the applicability of ADDA, a new DDA code for calculating scattering parameters of frozen hydrometeors at microwave frequencies. In addition it is investigated how many dipoles have to be used to reach a certain accuracy. A further aim is to calculate scattering parameters of single ice crystals continuously from 1 to 300 GHz in order to investigate what influence shape and orientation have, and up to what size parameter equal volume ice spheres are applicable for approximations. Furthermore, the effect the choice of the index of refraction has on the single scattering parameters is also investigated.

The structure of the paper is as follows: the fundamentals of the dielectric properties of ice at microwave frequencies as well as the most common empirical models are described in Section 2. The DDA is shortly introduced in Section 3. The pristine ice crystal shapes for which the calculations have been carried out are specified in Section 4 and the results are given in Section 5. Finally, the summary and the conclusions are presented in Section 6.

2. Dielectric properties of ice

The dielectric properties of ice are fundamental for the scattering calculation of frozen hydrometeors. They are strongly dependant on frequency and temperature. The dielectric properties of any material or substance can be described either by its index of refraction n or by its permittivity ϵ and permeability μ.

The refractive index is a complex value of the form

$$n = n_r - jn_i \tag{1}$$

The real part n_r determines the phase velocity v of the wave in the material in the form

$$v = c / n_r \tag{2}$$

where

c speed of light in vacuum (m/s)

The imaginary part n_i of the complex refractive index determines the attenuation of the wave as it propagates through the medium. The complex refractive index can be calculated from permittivity and permeability. The interrelationship is:

$$n = c\sqrt{\varepsilon \cdot \mu} = \sqrt{\frac{\varepsilon \cdot \mu}{\varepsilon_0 \cdot \mu_0}} = \sqrt{\varepsilon_r \cdot \mu_r} \tag{3}$$

where

c speed of light in vacuum (m/s)
ε_0 permittivity of free space
μ_0 permeability of free space
ε permittivity of the material or substance
μ permeability of the material or substance
ε_r relative permittivity of the material or substance
μ_r relative permeability of the material or substance

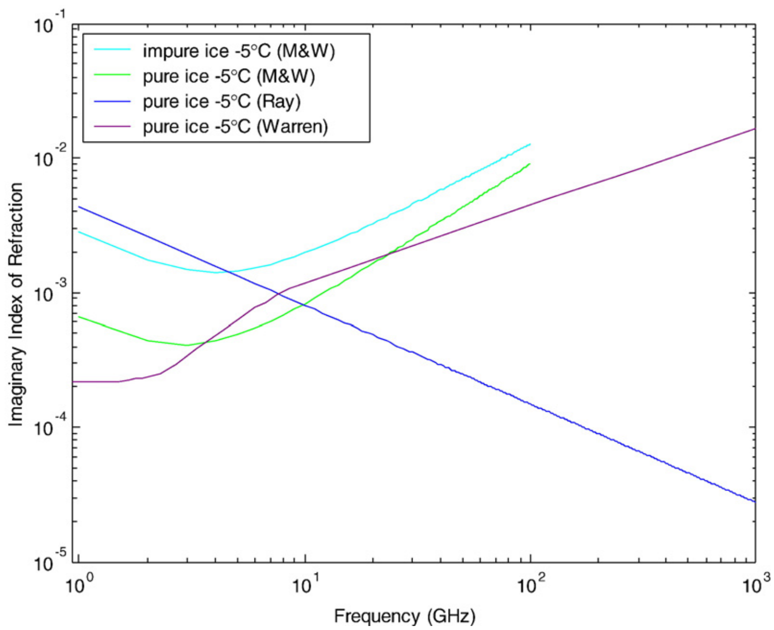

Fig. 1. Imaginary index of refraction of ice at microwave frequencies, according to various investigators.