A Fast Model for Microwave Scattering by Nonspherical Particles

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Motivation

Aggregate snowflakes are large, irregular hydrometeors which comprise a substantial portion of in-cloud ice. Modeling their scattering properties (e.g. backscatter cross sections) is important. Several techniques, such as the discrete dipole approximation (DDA) and the T-matrix method (TMM) are commonly used to model such properties. In recent years, the DDA has been the algorithm of choice for large, dense aggregates (Figure 1). A snowflake's volume is represented using a fine lattice, and the DDA represents each volume element as a dipole and determines the electromagnetic response of all of these dipoles. This approach is accurate, though very slow, as the radiative response must account for multiple scattering among lattice sites. The need for modeling many aggregate particles at many frequencies limits the DDA's feasibility.

The TMM typically assumes a homogeneous smooth shape, such as a sphere or ellipsoid. It preserves mass and, through the effective medium approximation, a measure of density. It is several millions of times faster than the DDA. However, it usually provides substantially different backscatter cross sections (Figure 2). By improving how we parameterize an aggregate's effective density, we present an algorithm that yields results that agree much better with the DDA. Eventual applications of this approach may include: fast and reasonable backscatter results for many aggregate morphologies (e.g. radar validation) at many frequencies (e.g. for dual- and triple-frequency analysis), and for very large and melting particles.

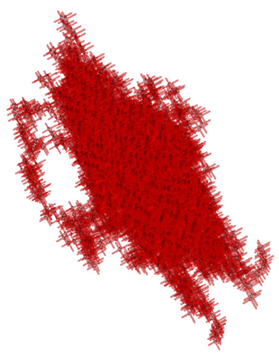

Figure 1 - An example of a bullet rosette aggregate found in our database.

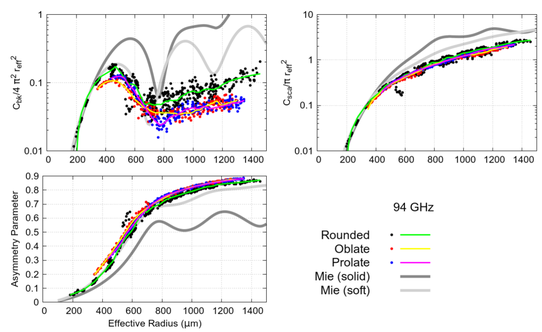

Figure 2 - Mie theory results (curves) compared with DDA results (points) at 94 GHz for Honeyager et al. [2016] aggregates. Top left: normalized backscatter cross section; top right: normalized scattering cross section; bottom: asymmetry parameter. Solid sphere Mie theory is shown in dark gray, and Mie results for constant-density 0.1 g/cm³ spheres are shown in light gray. Mie theory is a special case of the TMM for spheres.

Aggregate Model

- Our aggregate particles are agglutinations of 6-armed bullet rosette monomers (see Figure 1). Two sizes of bullet rosettes are used, with diameters of 200 and 400 μm. These bullet rosettes closely match the size / density relation observed in Heymsfield et al. [2002].
- When aggregated, the resulting particles agree with the Brandes et al. [2007] relationship to within 20%; the size-density relation also closely matches recent observations from Tiira et al. [2016].
- Three different aspect ratio formulations are considered. Generally spheroidal particles, possessing aspect ratios near 0.8 – 1, correspond to observations from Magono and Nakamura [1965] and Brandes et al. [2007]. There are 557 rounded aggregates. Additionally, 240 oblate and 180 prolate aggregates are also considered, with aspect ratios around 0.6. These correspond to observations from Brandes et al. [2007].
- Aggregate results are publicly available from our website (cirrus.met.fsu.edu) and through contacting the authors. Our database provides single scattering properties at ten frequencies from 10.65 to 183.31 GHz at 263 K.

Improvements in Density Parameterization

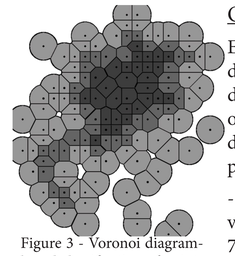

Figure 3 - Voronoi diagram-based classification of points into interior (dark and medium gray) and surface (light gray) points.

Our idea

Each aggregate lattice is analyzed by constructing its truncated Voronoi diagram. Each ice-filled lattice site is used as a generating point, and the diagram shows how different ice elements are spatially connected to each other. If a point has no neighbors on a particular side within a specified distance, then this point is classified as being on the 'surface'. All other points are on the 'interior' (Figure 3). Two approaches are considered:

- The contour of the interior region has a known mass and a known volume. Density = mass / volume, and the interior contains, on average, 75% of each aggregate's mass. We approximate the remaining 25%'s density in Honeyager et al. [2016] with a linear relation.
- We can contour the surface points using the Power Crust algorithm [Amenta et al. 1998], and define effective density with this contour (Figure 4).

What we compare performance with:

Our two density formulations were compared against five others: a constant 0.1 g/cm³ density approach; a circumscribing sphere approach with diameter matching the distance between the two furthest ice particles (used in Heymsfield et al. [2002], Liu [2004] and Liao et al. [2013]); a circumscribing ellipsoid (Matrosov [2007], Kniefel et al. [2011], Tyynela et al. [2011], Hogan et al. [2012]); the root mean square approach (Petty and Huang [2010]); and a radius of gyration approach (Osharin [1994], Westbrook et al. [2006]).

All calculations use the dielectric relation of Bohren and Battan [1980].

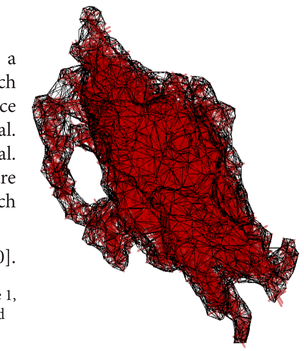

Figure 4 (right) - Aggregate from Figure 1, overlaid with a surface contour identified using the Power Crust algorithm.

Comparison

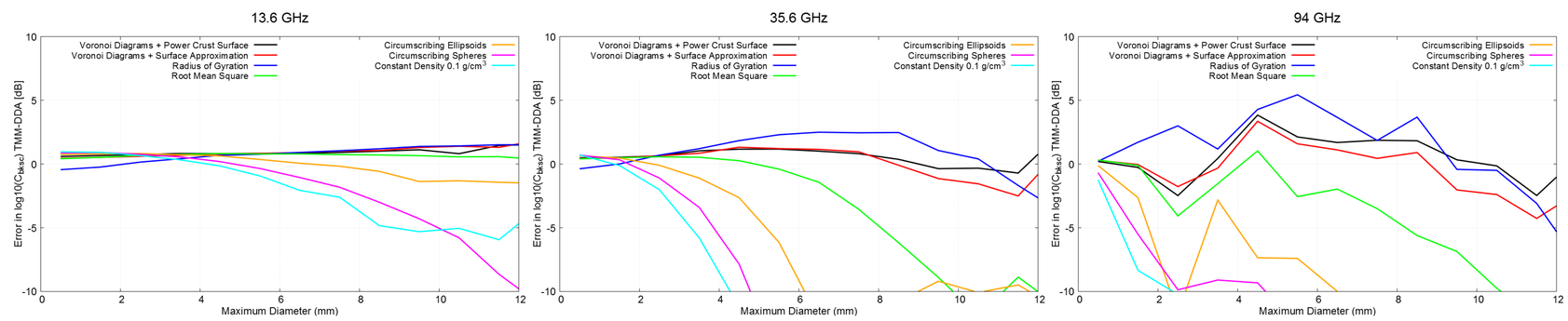

Figure 5 - Error, in decibels, of TMM backscatter relative to the DDA. Results are grouped into bins according to maximum flake diameter, shown on the x axis. Three radar frequencies are shown, corresponding to the K_u, K_a, and W bands.

In Figure 5:

- At the Rayleigh regime, it is evident that the Bohren and Battan [1980] dielectric does not perform well for bullet rosette aggregates. An alternate dielectric for bullet rosette aggregates is presented in Hogan, Honeyager and Tyynelä [2017], but the application to the TMM is ongoing.
- At 35.6 GHz, the constant, CS, CE and RMS approaches substantially underestimate backscatter for aggregates above 2-6 mm in length. Error eventually exceeds -10 dB. The Voronoi diagram-based methods provide an excellent match to DDA's backscatter throughout all of this domain.
- At 94 GHz, there is a strong resonance peak in both DDA and TMM results near 2-3 mm. Mispredictions of the peak location dominate the error here. Above 6 mm, the Voronoi diagram-based methods perform the best, with error to within 3 dB.

Figure 6 shows the error (expressed in percent) of the volume-integrated backscatter assuming the Sekhon-Srivastava [1970] particle size distributions.

- The Voronoi-based methods have the lowest relative error.
- This error is mostly independent of snowfall rate.

DDA computation times averaged one particle / (frequency * temperature * day * 12 processor cores). All corresponding TMM results were computed within one hour on a single-core machine.

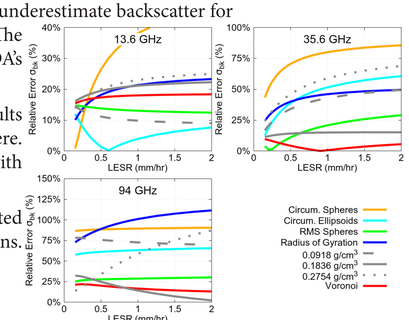

Figure 6 - Relative error (%) in the volume-integrated backscatter cross sections at three frequencies. Assuming the Sekhon and Srivastava [1970] size distribution, as a function of liquid-equivalent snowfall rate.

Conclusions

Two improved density estimation methods were developed and used to improve the accuracy of T-matrix backscatter calculations for aggregate snowflakes. These methods were tested against aggregates that were constructed from realistic monomers and obey observed particle size / density and aspect ratio relations.

The improved methods estimate density by separating a particle's mass into internal and surface regions, and then establishing closed contours to define the volume used in calculating density. This approach avoids the unphysical decline in backscatter observed in other effective medium sphere calculations. At 13.6 and 35.6 GHz, error is within 2 dB of discrete dipole approximation-calculated values, and this error is dominated by issues with the effective medium formulation (i.e. not with the density parameterization). At 94 GHz, error is within 4 dB. When a particle size distribution is used, the percent error in integrated backscatter is always within 25%. Due to its superior accuracy and performance, the use of these techniques are suggested for for applications where backscatters for many varied aggregate models are desirable.

All references here are listed in the adjacent papers, which present a more in-depth discussion.