Modeling Snowflakes at Microwave Wavelengths

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With the advent of satellite-borne radar and radiometers, it is now possible to observe ice cloud processes with unprecedented levels of precision. Unlike liquid water, ice exhibits many complex shape and orientation-dependent effects. We examine how particle shape affects single-scattering behavior of hydrometeors at microwave wavelengths.

Generally, a hydrometeor's scattering and backscatter behavior can be considered as a function of the its size and shape, which can be expressed using mass and surface area. Existing tables for calculating scattering by hydrometeors usually consider idealized forms, such as spheroids, dendrites, hexagonal plates, rosettes and sector snowflakes.

Many current and prior field studies have included measures of particle mass and a single-angle picture. We constructed aggregates that match observations with regards to particle size, aspect ratio, density and fractal dimension. We consider the relative importance of models of the internal structure of a hydrometeor versus surface features. We use this information to then derive generalized trends for backscatter based on surface area.

An eventual goal of this research is to determine how an ice crystal scatters microwave radiation from one or more camera pictures.

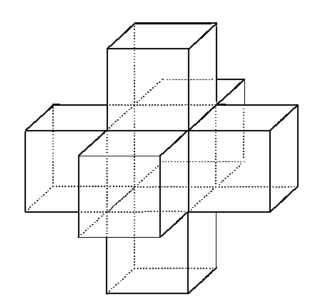


*Figure **1** - A bullet rosette*

Aggregate Generation

We used 6-bullet rosettes (Figure 1) as a base to generate aggregate particles (Figure 3) that match known particle size, density and aspect ratio relations (Figure 4).

- Base bullet rosettes are constrained to follow the size / density relationships from Heymsfield et al. [2002].
- Aggregates are generated using 200 micron, 400 micron and 200+400 micron diameter bullet rosettes.
- Overall aggregate is constrained to follow the size / density relationships in Brandes et al. [2007]

Aspect ratios (AR; width / thickness) considered (Figure 2):
- ~0.8-1 (spheroids) matching Magono and Nakamura [1965] and Brandes et al. [2007]
- ~0.6 (oblate ellipsoids) for Korolev and Issac [2007]
- ~1.67 (prolate ellipsoids)

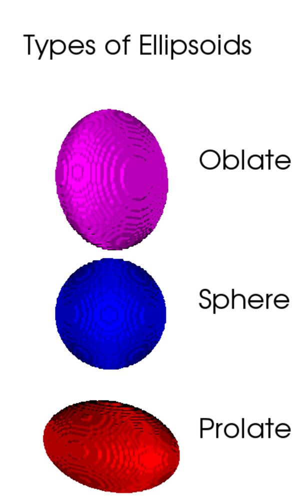
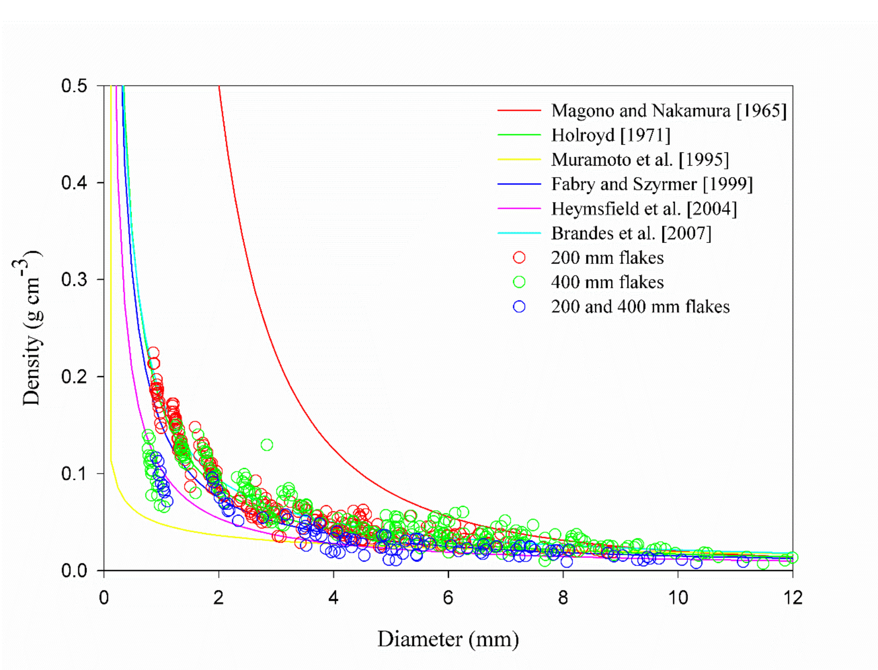


*Figure **2** - Spheroidal, oblate, and prolate ellipsoids*



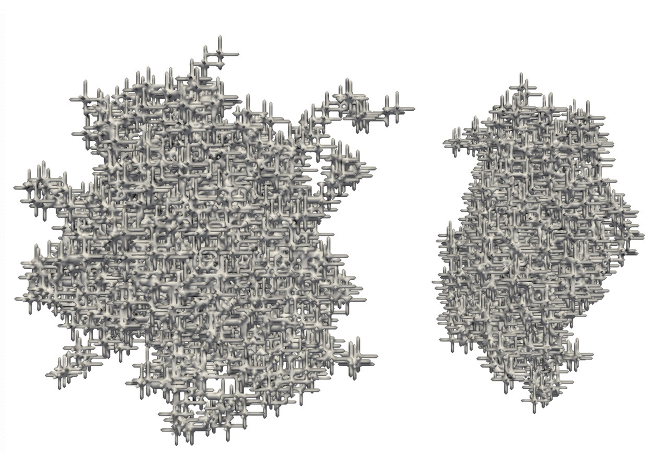


*Figure **3** (top) - 2d example view (front; side) of an oblate (AR 0.6) aggregate.*
*Figure **4** (left) - Size / density relationships from Brandes et al. [2007], plotted against spheroidal aggregates from this study.*

Single Scattering Properties

Aggregate flake single-scattering properties were calculated using the Discrete Dipole Approximation [Draine and Flatau 2013], at 36.5, 89 and 183.31 GHz. The same quantities are compared with equivalent-diameter spheres at 36.5 GHz using Mie theory.

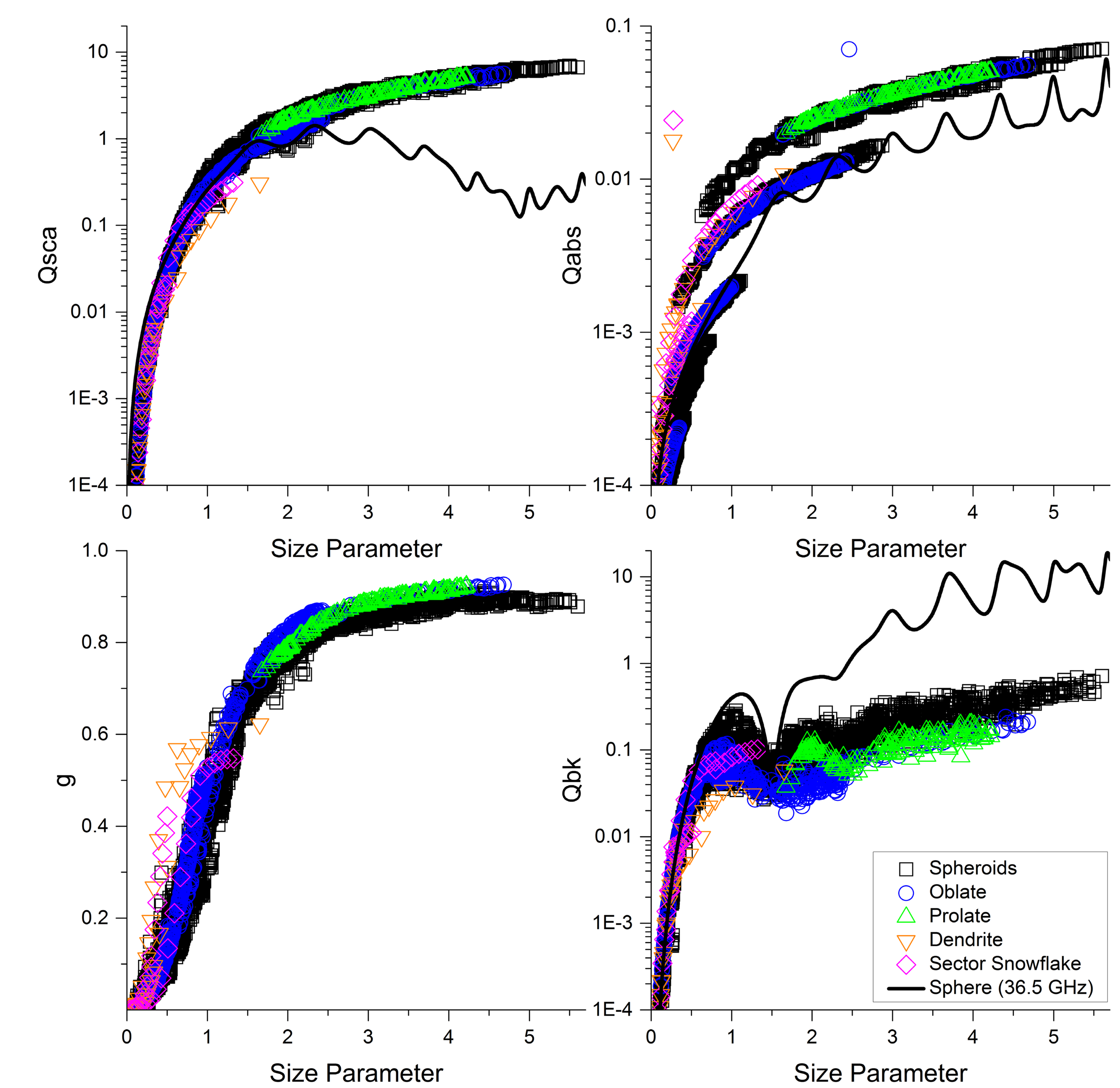


*Figure **5** - Single-scattering properties of spheroidal, oblate and prolate aggregates, as well as dendrite and sector snowflake hydrometeors.*

- Solid spheres do not closely match aggregate results. Symmetry leads to resonance effects.
- Absorption cross-section and asymmetry parameter are nearly identical for different particles.
- Backscatter varies by nearly one order of magnitude over different particle morphologies containing the same volume of ice.
  - With same shape (similar aspect ratios), variation is still over 100%.
  - Oblate and prolate flakes show markedly lower backscatter than spheroids.
- Scattering trend is similar, though less pronounced.

Summary

- Generated diffuse aggregates constrained by observational studies.
- Backscatter can be well-modeled as a function of surface area, mass (volume), temperature and frequency.
- Backscatter and scattering cross-sections are only weakly dependent on the modeling scheme used for ice particle interiors.
- Further observational studies should focus on measuring hydrometeor mass and surface area, not just aspect ratio. Multi-angle imaging is suggested.

Surface Area vs. Volume

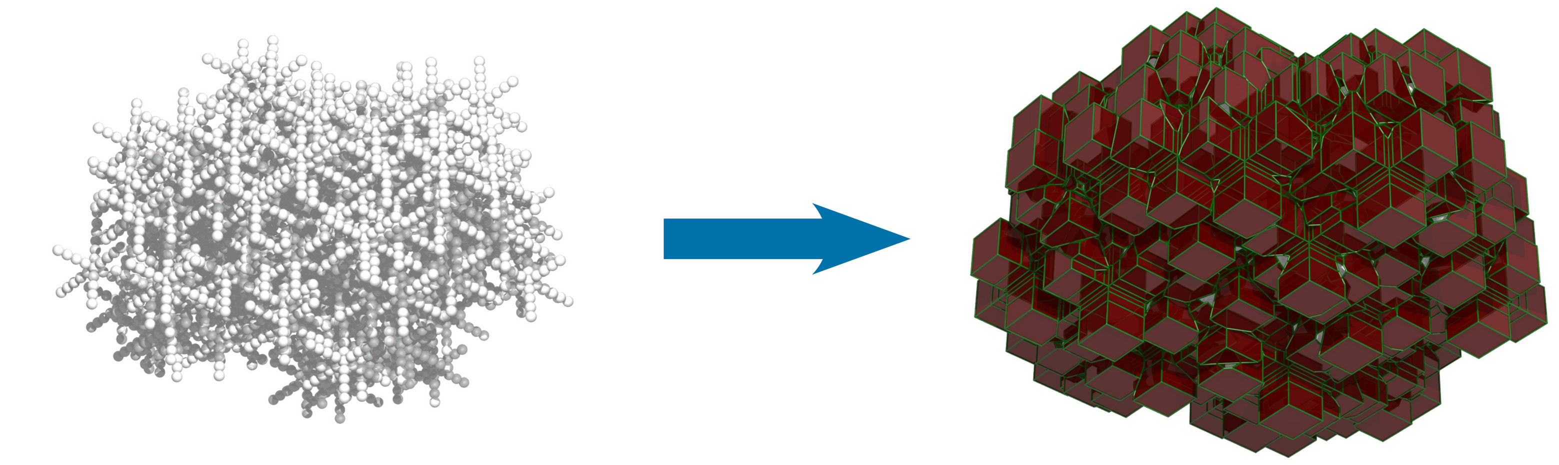


*Figure **6** - Initial flake (left) has an ill-defined surface. At microwave scales, we define an effective surface (right), with a well-defined surface area and enclosed volume.*

To further understand these scattering and backscatter trends, we extract a surface and particle interior using a Voronoi cell-based method (Figure 6) [Rycroft 2009].

- Sphere SA/V ratio is 3/R (non-constant and has dimensions).
- We instead take Voronoi SA/V ratio vs. ratio for solid ice sphere at same volume.
- Spheres have lowest possible SA/V ratio.
- Higher surface area results in a more complicated shape, making backscatter less likely.
- Surface area is easily approximated by multi-angle imaging.

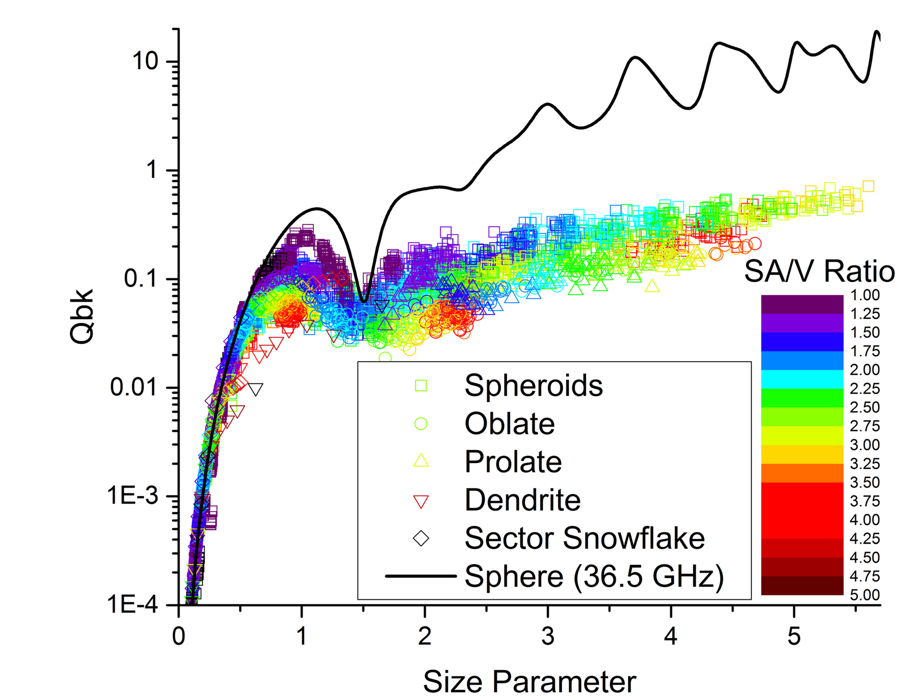


*Figure **7** (above) - Backscatter contoured by dimensionless ratio of ratios of Voronoi SA/V and equivalent solid ice sphere SA/V.*

Interior vs. Exterior

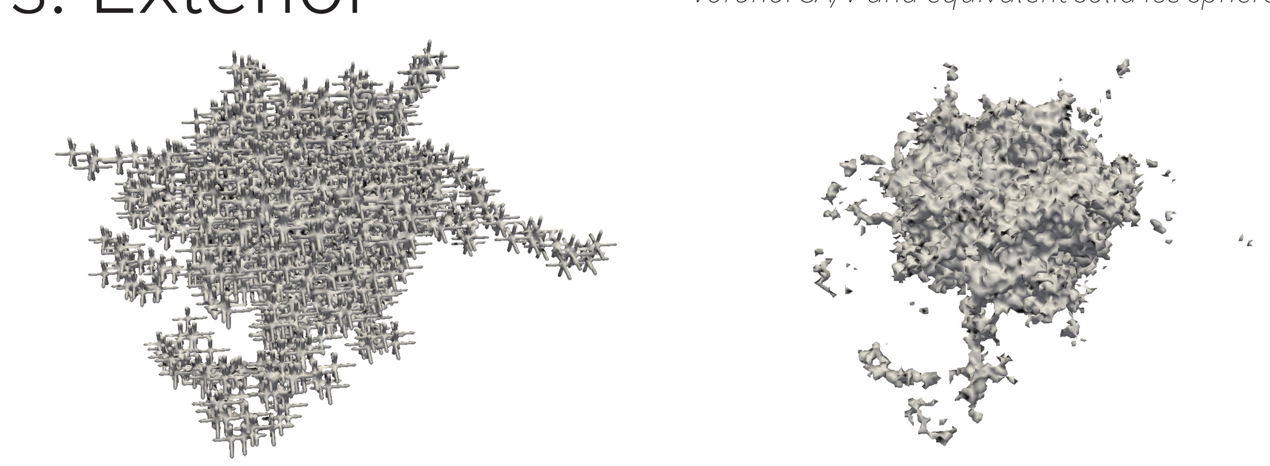


*Figure **8** - Surface and interior of a random aggregate. A Voronoi cell-based method determines the aggregate's interior, which is then randomized.*

Our aggregates are based on observational studies that lack information about hydrometeor interiors.
- After defining an aggregate surface, we defined an 'interior' of the particle - all potential lattice sites further than two Voronoi cells from the surface (Figure 8).
- Interior was randomized, representing a lack of all information about the interior except for overall particle mass.
- Despite changing 60-80% of all lattice sites in any given aggregate, scattering cross-section varied by only 2%, and backscatter varied less than 12% on average (Figure 9).
- Compare with 100% change for same aspect ratio, different surface, and with 10x difference when constrained only by mass.

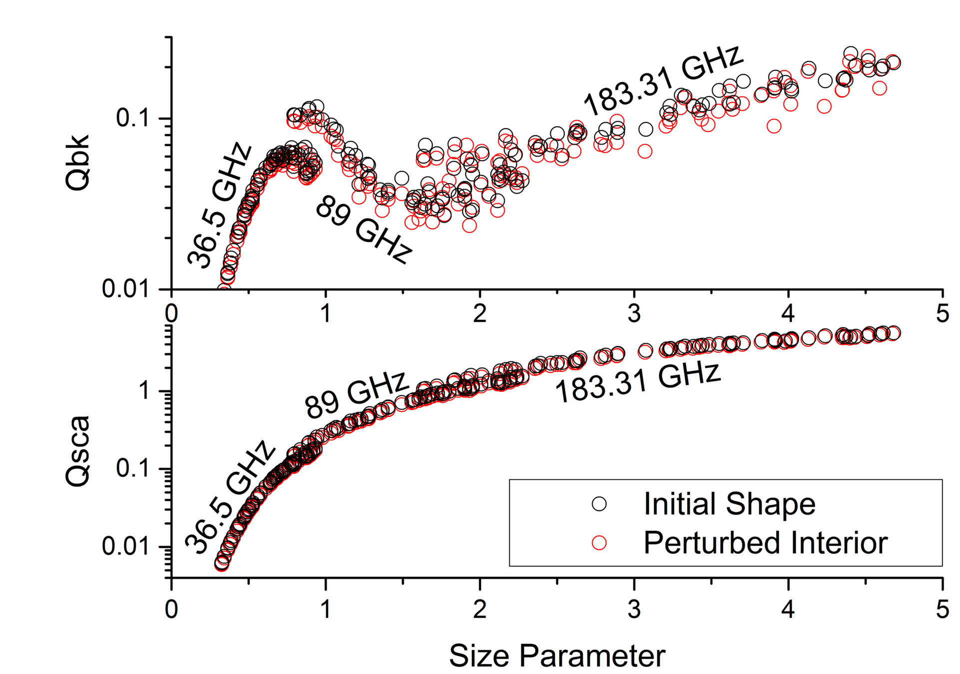


*Figure **9** - Backscatter and scattering cross-section comparison of interior-perturbed and unperturbed oblate aggregates. Flake pairs have identical sizes and surfaces, but different interiors.*