Manual for the scattering database

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1 Content of the database

This database includes results of scattering computations for dry and pristine single ice crystals, their aggregates, and graupel at microwave frequencies between 2.7 (S band) and 220 GHz (G band). The single ice crystals are preferentially oriented, while the aggregates and graupel are in random orientation. All particles have their orientation fixed for the scattering computations, which means that the scattering properties have not been averaged in any way and therefore include all phase-related features of the incident and scattered wave. I recommend averaging over the random samples, when using these particle properties.

2 Use of the database

I provide this database 'as is' and freely to use and experiment. If the results are used in a scientific paper, the only thing I ask is to refer to our paper (*Tyynelä and Chandrasekar* (2014)), which introduces the computations.

Any bug reports or questions about database can be emailed to janityynela(at)gmail.com.

3 Data structure

The data arrays in the database have been produced with Matlab and the output format is NetCDF (version 4.1.3). There are individual NetCDF files for each frequency band, each snowflake type, and each type of property. For the frequency, possible values are: `'S'` (2.7 GHz), `'C'`(5.6 GHz), `'X'` (9.8 GHz), `'Ku'` (13.6 GHz), `'Ka'` (35.6 GHz), `'W'` (94.0 GHz), and `'G'` (220.0 GHz). For the snow types, values are: `'hexcolum_crystal'`, `'hexplate_crystal'`, `'steldend_crystal'`, `'needle_crystal'`, `'rosette6_crystal'`, `'graupel'`, `'steldend_aggregate'`, `'ferndend_aggregate'`, `'needle_aggregate'`, and `'rosette6_aggregate'`. For the particle properties, values are `'cross'` (cross sections), `'phys'` (physical properties), and `'phase'` (phase function).

The naming format of the files is:

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[author name] _ [creation date] _ [particle property] _ [frequency band] _ [snow type].nc
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3.1 Cross sections

For the cross sectional data, we have `'chh'` and `'cvv'` as the linearly co-polarized horizontal and vertical backscattering cross sections, respectively, `'cvh'` as the linearly cross-polarized backscattering cross section, `'crr'` and `'crl'` as the circularly co- and cross-polarized backscattering cross sections, `'csca'`, `'cabs'`, and `'cext'` as the total scattering, absorption, and extinction cross sections for unpolarized incident wave, respectively, and `'asym'` as the asymmetry parameter for unpolarized incident wave. The units are square meters m^2 for all cross sections. Asymmetry parameter is dimensionless.

For the single ice crystals, the dimensions of the arrays are the number of elevation angles `'nelev'`, and the number of sample particles `'nsmpl'`. For the aggregates, the dimensions are the number of ice crystals `'ncr'` and the number of sample particles `'nsmpl'`. For the grauples, the dimensions are the number of iterations `'niter'` and the number of sample particles `'nsmpl'`.

3.2 Physical properties

For the physical properties, we have `'ncryst'` as the number of ice crystals in an aggregate, `'ndip'` as the number of dipoles, `'dmax'` as the maximum diameter in units of meters m, `'area'` as the geometric cross section in units of square meters m^2, `'ar'` as the aspect ratio, `'mass'` as the mass in units of kilograms kg, and `'round'` as the roundness.

For the single ice crystals, the dimension of the arrays is the number of sample particles `'nsmpl'`. For the aggregates, the dimensions are the number of ice crystals `'ncr'` and the number of sample particles `'nsmpl'`. For the grauples, the dimensions are the number of iterations `'niter'` and the number of sample particles `'nsmpl'`.

3.3 Phase functions

The phase functions are stored as `'phasefunc'`. For the single ice crystals, the dimension of the arrays are the number of elevation angles `'nelev'`, the number of sample particles `'nsmpl'` and the number scattering angles `'nang'`. For the aggregates, the dimensions are the number of ice crystals `'ncr'`, the number of sample particles `'nsmpl'`, and the number scattering angles `'nang'`. For the grauples, the dimensions are the number of iterations `'niter'`, the number of sample particles `'nsmpl'`, and the number scattering angles `'nang'`. The number of scattering angles is 181 in 1 degree intervals between 0 and 180.

Note that the phase function p is normalized as

$$\int_0^{\pi} \int_0^{2\pi} p(\theta, \phi) sin(\theta) d\theta d\phi = 1, \tag{1}$$

where θ is the scattering angle and ϕ the azimuth angle. For an unpolarized incident wave, $p = P_{11}/(\sigma_{\text{sca}} k^2)$, where P_{11} is an element in the scattering matrix, σ_{sca} the scattering cross section, and k the wavenumber of the incident wave.

Due to the fixed orientation for each sample particle, the ADDA program outputs the scattering matrices between 0 and 360 degrees for the scattering angle. However, since the phase function is defined only between 0 and 180 degrees for the scattering angle, I have averaged over these two hemispheres. Note that there is no other averaging over the azimuthal angles. This is accomplished by choosing uniformly random direction for the azimuth angle during particle generation.

4 Modeling

4.1 Shape modeling

There are five single crystal types: hexagonal column, hexagonal plate, needle, ordinary dendrite, and six-bullet rosette. The thickness-to-diameter and length-to-diameter ratios are taken from *Pruppacher and Klett* (1997) for the different types of ice crystals (see Table 1).

Needles are modeled as long circular cylinders. For the dendrites, I use the crystal growth algorithm by *Reiter* (2005). It is based on a 2-D cellular automaton using two parameters that control the amount of water available for the cells both locally and globally. For the six-bullet rosettes, I adopted the shapes by *Um and McFarquhar* (2007).

The lump graupels are modeled with the fractal algorithm by *Ishimoto* (2008). In the fractal model, the snowflake is generated using an iterative method, which adds ice cells into a cubic lattice. The amount of ice added is controlled by two parameters: the fractal dimension f_D and the total number of iterations. In order to fit the measured mass-diameter relationship by *Heymsfield and Kajikawa* (1987) for graupel, I choose the fractal dimension $f_D = 2.7$. This value is close to the maximum possible with the current implimentation. For the number of iterations, I use 4, 5, 6, and 7.

For the aggregates, I use the physically-based aggregation model by *Westbrook* (2004). It mimics the aggregation process in a stochastic way by iteratively determining the probability of collision between randomly chosen ice crystals, which depends on the size and fall speed of the candidates. Due to the lack of observations, I assume random orientation and a narrow Gaussian size distribution for the ice crystals in an aggregate because of the complex flow around the snowflakes. The ice crystals are attached without

Table 1: Snowflake properties for the computations.

Snowflake type	D_{max} [mm]	D_0 [mm]	Dimensions [cm]	Number of crystals
hexagonal column (N1e)	0.1–2.0	0.5–1.4	$d = 0.03527\ L_{max}^{0.437}$	1
hexagonal plate (P1a)	0.1–2.0	0.6–1.5	$h = 0.0141\ D_{max}^{0.474}$	1
needle (N1a)	0.3–3.0	1.4–2.0	$d = 0.030487\ L_{max}^{0.61078}$	1
ordinary dendrite (P1e)	0.4–4.3	1.7–3.0	$h = 0.009022\ D_{max}^{0.377}$	1
fernlike dendrite (P1f)	0.9–7.0	3.0–5.3	$h = 0.009022\ D_{max}^{0.377}$	1
six-bullet rosette (C3b)	0.2–1.4	0.6–1.0	$d = 0.0151\ L_{max}^{0.455}$	1
lump graupel (R4b)	0.5–5.0	0.6–1.2	–	–
aggregate of needles	0.3–8.0	1.8–5.2	–	2, 10, 20, 30, 40, 50
aggregate of ordinary dend.	0.6–17.8	1.6–10.0	–	2, 10, 20, 30, 40, 50
aggregate of fernlike dend.	1.4–24.0	5.0–14.6	–	2, 10, 20, 30, 40, 50
aggregate of rosettes	0.3–4.4	1.1–2.6	–	2, 5, 10, 15, 20

overlapping to their nearest neighbour. For the aggregates of needles, I use the method by *Kajikawa et al.* (2000) to attach similar sized crystals.

There are four aggregate types: needles, ordinary dendrites, fern-like dendrites, and six-bullet rosettes, i.e. 4 out of 5 pristine types. The number of crystals (or monomers) in each aggregate is varied and depends on the ice crystal type. For needles and dendrites, we use 2, 10, 20, 30, 40, and 50 monomers, while for the six-bullet rosettes, we use 2, 5, 10, 15, and 20.

As single ice crystals tend to fall in preferential orientation (*Cho et al.* (1981); *Thomas et al.* (1990); *Matrosov et al.* (2005); *Noel and Sassen* (2005)), I orient the generated ice crystals according to the measurements by *Noel and Sassen* (2005) for warmer clouds, which indicate highly horizontal orientation with an average canting angle of about 2° and a Gaussian distribution with a standard deviation of 1°. It should be noted that these values are based on observations of planar crystals and may not be representative of all the types used here. The orientation of the aggregates and graupel is assumed to be random.

4.2 Scattering modeling

The scattering properties are computed using the discrete-dipole approximation (DDA), which is a method where the particle is divided into small volume elements (dipoles) that are placed into a regular cubic lattice (*Purcell and Pennypacker* (1973)). This allows a high degree of detail in the particle shape, which can be controlled by the number of volume elements used in the shape model. The accuracy of DDA is determined both by the number of dipoles and the dipole spacing kd relative to the wavelength (k is the wavenumber of the incident wave). It is usually required that $|m|kd < 1.0$, where m is the refractive index of the material (*Draine* (2000)). I have fixed d to 20 μm for all particles, except the fern-like dendrites, which have $d = 40$ μm, and $|m|kd$ is 0.58 at maximum. The refractive index of solid ice is taken from *Jiang and Wu* (2004). The ADDA program by *Yurkin et al.* (2011) is used to compute all the scattering properties in this database.

To simulate a radar volume, I have generated 1000 individual ice crystals for each type randomly chosen within the appropriate size range, and 100 random aggregates of ice crystals for each type and for each number of crystals in the aggregate. To generate the graupels, I use 100 random fractals for each number of iterations. The total number of different snowflakes in the database is 7700. The details of these numbers are also shown in Table 1. Due to the preferential orientation of the ice crystals, the elevation angle of the radar is varied: 0°, 15°, 30°, 45°, 60°, 75°, and 90°.

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