Closure study of microphysical and scattering properties of snowfall using data from the ARM - BAECC 2014 campaign in Hyytiälä Finland

Ori[1], Davide, D. Moisseev[2], A. von Lerber[2], J.Tiira[2], G. Huang[3], J. Leinonen[4], V. Chandrasekar[2,3],
[1]University of Cologne, Germany; [2]University of Helsinki, Finland, UK; [3]Colorado State University, Fort Collins CO, USA; [4]JPL, USA;

1. Motivation

Snow particle properties exhibit a large variability (size, density, mass, fall velocity, shape, scattering properties) and the relations among those properties are still poorly understood.
- Is it possible to establish a modeling framework that consistently match multiple coincident snow observations?

The availability of snowflake scattering databases is continuously increasing, but they are difficult to introduce since the effects scattering properties are hard to separate from PSDs and mass in integral measurements such as radar reflectivity
- How we can verify and compare scattering calculations?
- Is it possible to use ground observation to constrain the scattering calculations?

The connection between physical snowfall properties and radar observations is not always straightforward
- Is it possible to use multiple coincided measurements to establish a robust relation between snowfall physical and scattering properties?

2. The BAECC campaign

The ARM-BAECC campaign constitutes a unique opportunity to investigate the connection between the microphysical and scattering properties of snow thanks to the extensive deployment of ground measurements and three co-located vertical pointing radars at X, Ka and W band.
The list of instruments and relative provided measurement significant for the present study is given:

Figure 1: Instrument configuration during the ARM-BAECC campaign (winter 2014).

INSTRUMENT	MEASUREMENT
2xPluvio gauges	SR
PIP	N(D), v(D)
2DVD	N(D), v(D)
XSACR	X band reflectivity
KaSACR	Ka band reflectivity
KAZR	Ka band reflectivity
MWACR	W band reflectivity

3. Derivation of snowfall microphysical properties

3.1 Snow Rate driven retrieval

$$m(D)=\alpha D^{\beta} \qquad v(D)=\delta D^{\gamma} \qquad (1)$$

m-D and v-D relations are commonly assumed to be in the form of power laws (eq. 1).
Using this formulation, given the range of observations of the BAECC campaign it is possible to find values of the m-D relation parameters that gives consistent results among the different measurements.

Snow Rate:
$$SR=\int m(D)v(D)N(D)dD \qquad (2)$$

Rayleigh Reflectivity:
$$Z=\frac{|K_i|^2}{\rho_i^2|K_w|^2}\int \rho^2(D)D^6N(D)dD \qquad (3)$$

$$\rho_{SR}=\frac{SR}{\pi/6\int D^3v(D)N(D)dD} \qquad (4)$$

$$\rho_Z^2=\frac{Z}{\frac{|K_i|^2}{\rho_i^2|K_w|^2}\int D^6N(D)dD} \qquad (5)$$

In particular it is possible to derive the formulation for ensemble mean densities (Tiira, et al. 2016) weighted upon SR and Z respectively (eq. 4,5). The ratio of these two squared quantities depends only on some non-integer order moments of the PSD:

$$\Delta Z=\frac{\rho_{SR}^2}{\rho_Z^2}=\frac{M_{\beta+\delta}^2M_6}{M_{3+\delta}^2M_{2\beta}} \qquad (6)$$

This quantity evaluate the discrepancies between the measured Rayleigh reflectivity and Z computed using spheroids of constant density as retrieved by in-situ observation of the snow rate.
A peculiar feature of this formulation is that it does not depend on the prefactor parameter α of the m-D and allows a direct inversion of the expression to derive β.
The analytical expression of ΔZ as a function of β and δ is given in figure 2 under the assumption of an inverse exponential PSD. Figure 2 also gives an indication of the sensitivity of the β retrieval to uncertainties in the measurement of δ or Z.

Ensemble mean densities

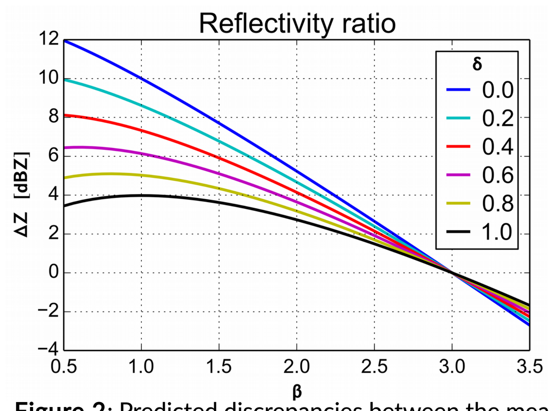

Figure 2: Predicted discrepancies between the measured reflectivity and *Z* simulated using *SR* weighted ensemble mean density assuming inverse exponential *N(D)*.

3.2 General hydrodynamic theory

The availability of a 2D-video disdrometer gives the opportunity to test the results of the microphysical retrieval by applying the general hydrodynamic theory (Böhm, H.P. 1989) to a completely independent dataset.
This method retrieves the single particle mass by inverting the fall velocity formula that relates the terminal fall speed of a particle to its mass and area ratio. A best fit in the form of a power law is derived every 20 minutes to guarantee a sufficient amount of particles to be included in the fitting procedure.
The same technique is also applied to the PIP data. Due to the larger collection area of the PIP instrument it has been possible to derive a robust fit every 5 minutes (von Lerber, et al. 2017).

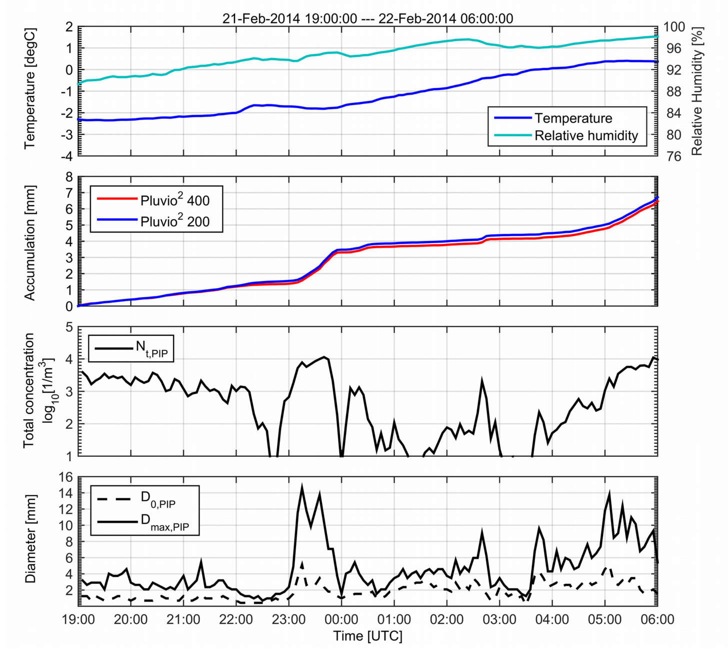

Figure 3: Temperature and relative humidity, liquid equivalent snow accumulation measured with both Pluvio gauges and the PSD parameters, total particle concentration, median volume and maximum measured diameter during the event of 21/22 February 2014

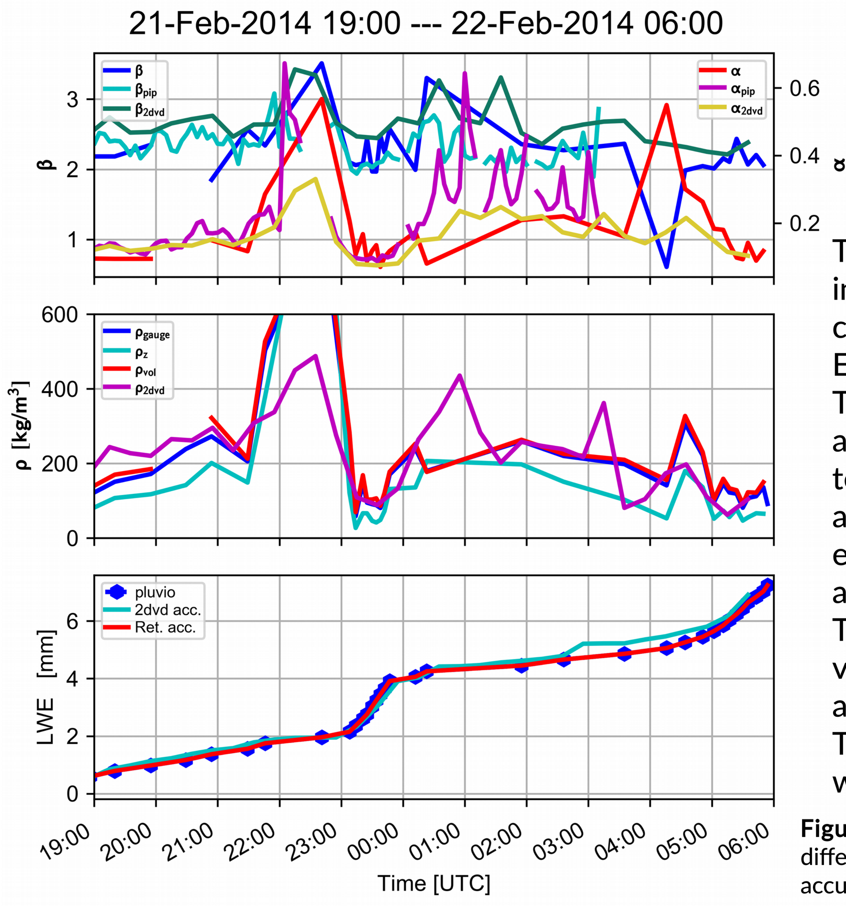

Figure 4: From top to bottom. Microphysical properties (α, β) as retrieved using the three different methods. Different definitions of the ensemble mean density. Snow gauge accumulation calculated using the retrieved microphysical parameters.

3.3 Results

The results of the three different retrieval methods are shown in figure 4. The three retrieval methods give results that are comparable with each other.
Each retrieval technique show strength and weaknesses.
The SR or gauge driven retrieval is limited by the gauge accumulation resolution and during period of low snow rate it tends to incorporate many different particle types breaking the assumptions of the retrieval method (equations 1), but it ensures to provide results that are consistent with snow accumulation and X-band reflectivity.
The 2DVD technique has an high accuracy in the particle fall velocity measurement, but it suffers from the small capturing area of the 2DVD instrument.
The PIP method gives the results that are in better accordance with previous published literature (β≈2).

4. Constrain scattering properties using m-D

4.1 Discrete Dipole Approximation

The scattering database published by Leinonen and Szyrmer (2015) has been used to simulate the radar reflectivity at X, Ka and W band.
The size-resolved scattering properties of snowflakes has been derived from the database by matching the single particle microphysical properties with those obtained by the microphysical retrieval algorithm.

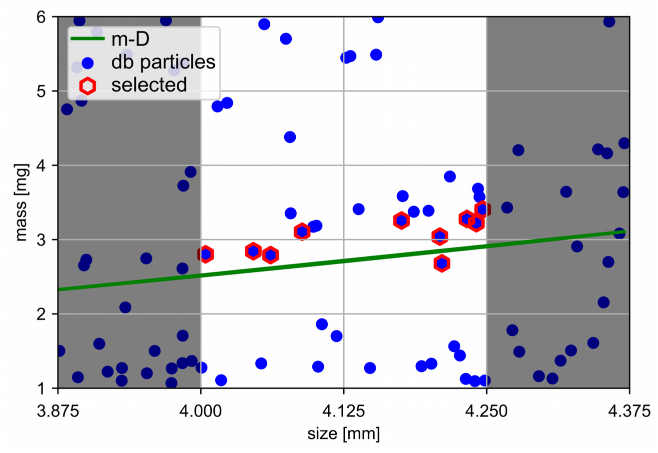

Figure 5: Schematics of the particle selection method applied to choose the modeled snowflakes from *Leinonen (2015)* database.

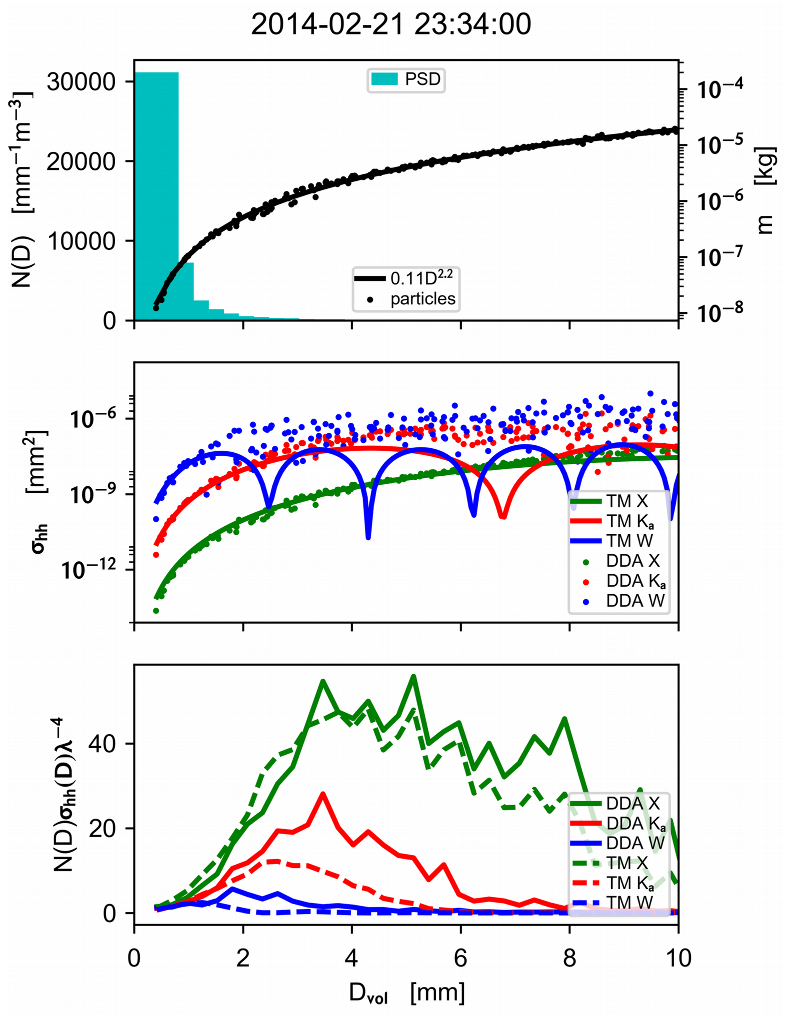

Figure 6: Size resolved microphysical and scattering properties of snow particles for a particular time period. From top to bottom: measured PSD, retrieved m-D relation and masses as a function of size of the selected particles. Modeled radar backscattering cross section using DDA and T-Matrix. Size distribution of modeled radar signal.

The method used to calculate the radar reflectivity using the DDA database is described by the figure 5 schematics and the following step procedure:
- For each PSD size range:
    1) Select size range in the DB
    2) Compare with m-D
    3) Pick the best fitting particles and average the scattering properties
- Integrate the results over the PSD

4.2 T-Matrix Method

As a dual of the retrieved m-D relation the ρ-D gives the volume fraction of ice with respect to air for each snowflake size. The particle shaped is set to be a spheroid of volume equal to $V=\pi D^3/6$ and aspect ratio fixed to 0.6
Ice volume fraction is used to derive the effective refractive index of the ice-air mixture composing the spheroid using the well-known Maxwell-Garnett approximation considering ice as inclusion in air matrix

5. X, Ka, and W reflectivity simulations

Given the assumption of the microphysical retrieval (section 3.1) the correspondent TMM synthetic reflectivity coincide with the X-band radar measurements (top panel figure 7). The other methods give comparable results.

The DDA method tends to emphasize the scattering properties of larger particles (third panel figure 6) and this feature. When large particles comprises the PSD (see figure 3), the DDA scattering solution gives larger Z that are larger than the measurement especially at higher frequencies.

The validity of the TMM method does not break at higher frequencies as expected.
Kneifel, et al. (2105) found for the same snow event the typical non-spheroidal behavior in the triple-frequency space. This discrepancy is likely to be related with the long time averages adopted for the study (5, 20 minutes and longer).

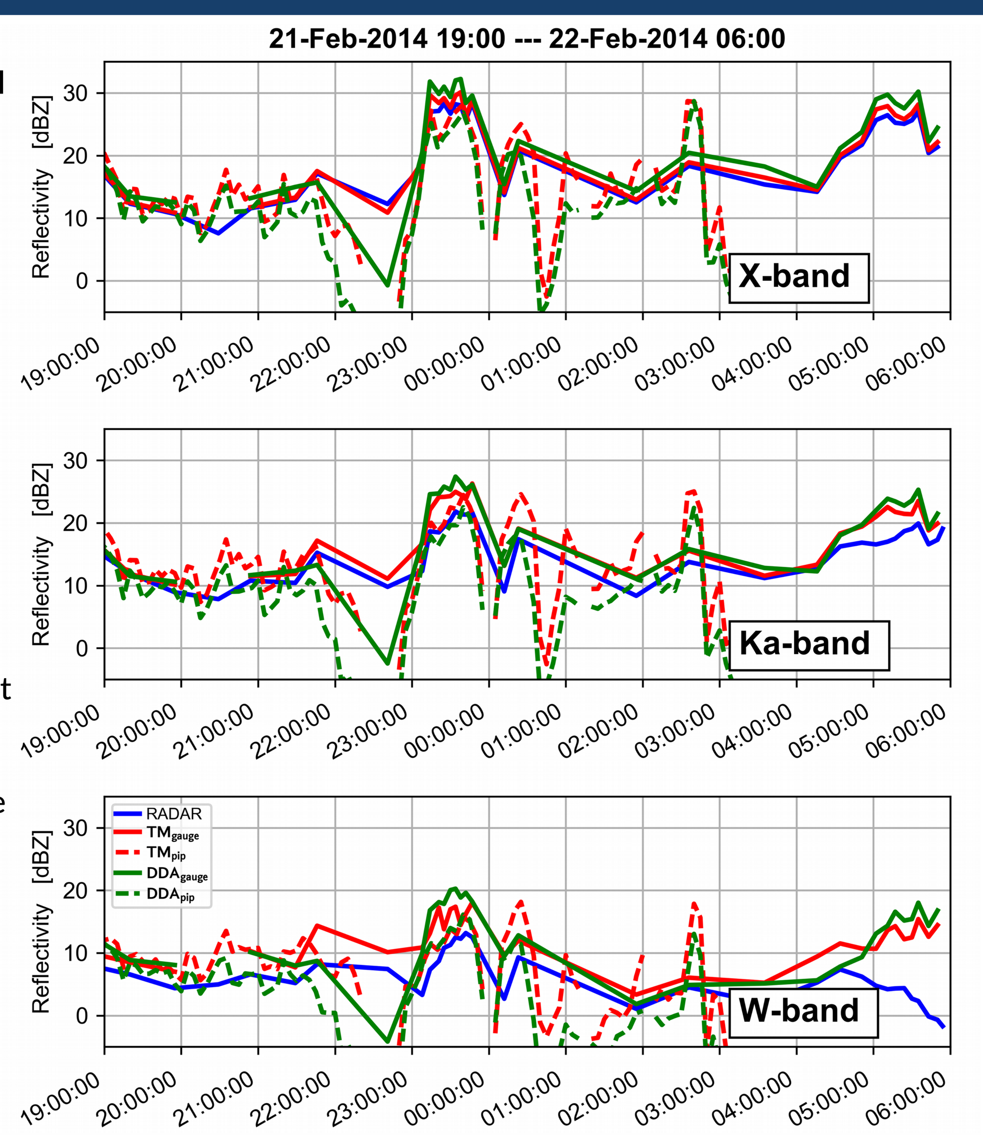

Figure 7: Triple frequency (X, Ka, W) simulation of radar reflectivity compared with radar measurements. DDA and T-matrix are used as scattering methods (respectively green and red curves). The underlying gauge and PIP microphysical retrieval are indicated respectively with continuous and dashed lines.

6. Summary

1) Three distinct microphysical retrieval methods based on ground and remote sensing measurements are compared.

2) It is possible to constrain the scattering calculations and simulate radar reflectivity at X, Ka and W band using modeled snowflake particle with proper microphysical characteristics and the TMM and DDA scattering methods.

3) The characteristic triple-frequency signature of non spheroidal snowflakes are difficult to see on large ensemble averages and the TMM approximation remains a valid technique in these situations.

4) Further studies are required to investigate the conditions where DDA accurate measurements are needed to fully describe snowflake scattering properties.

References:

Böhm, H.P., 1989: A General Equation for the Terminal Fall Speed of Solid Hydrometeors. J. Atmos. Sci., 46, 2419–2427, doi: 10.1175/1520-0469(1989)046<2419:AGEFTT>2.0.CO;2

Kneifel S., A. von Lerber, J. Tiira, D. Moisseev, P. Kollias, and J. Leinonen (2015): Observed Relations between Snowfall Microphysics and Triple-frequency Radar Measurements, *J. Geophys. Res.*, 120, 6034-6055, doi: 10.1002/2015JD023156.

Leinonen, J., and W. **Szyrmer** (2015): Radar signatures of snowflake riming: A modeling study, *Earth and Space Science*, 2, 346–358, doi:10.1002/2015EA000102.

von Lerber, A., D. Moisseev, L.F. Bliven, W. Petersen, A. Harri, and V. Chandrasekar, 2017: Microphysical Properties of Snow and Their Link to Ze–S Relations during BAECC 2014. J. Appl. Meteor. Climatol., 56, 1561–1582, doi: 10.1175/JAMC-D-16-0379.1

Tiira, J., Moisseev, D. N., von Lerber, A., Ori, D., Tokay, A., Bliven, L. F., and Petersen, W.: Ensemble mean density and its connection to other microphysical properties of falling snow as observed in Southern Finland, Atmos. Meas. Tech., 9, 4825-4841, doi: 10.5194/amt-9-4825-2016, 2016.