Retrieval of microphysical properties of snow using dual polarization spectral analysis: model and data analysis

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1 Summary

Snow crystals consist of many different types of ice particles. Typical radar measurements observe only bulk properties of all types of ice particles present in a radar volume. Due to their difference in radar cross-section, larger particles will reflect more power of the transmitted radar signal, than small particles. If small and large particles are present in the same radar volume with comparable volume concentration, the radar measurements will be dominated by larger particles. Because of this, it is difficult to obtain microphysical properties of both large and small particle types, based on reflectivity alone.

In this paper, the application of dual polarization spectral analysis for retrieval of microphysical properties of ice particles in stratiform precipitation is presented. Based on literature research, a selection on the particle types that are predominantly present in radar measurements is done. The selection is based on both radar cross sections of the different particles and meteorological conditions. The radar cross-sections are calculated with a model of the microstructure of ice crystals, derived from literature. With the obtained knowledge, it is shown that aggregates and plates dominate spectral radar retrievals above the melting layer of stratiform precipitation.

A model for the spectral horizontal reflectivity and spectral differential reflectivity of plates and aggregates, is created. This model is dependent on the parameters of the drop size distribution of plates and aggregates, the ambient wind velocity and spectral broadening. Using a sensitivity study of the spectral radar observables on the drop size distribution parameters, an algorithm is developed that is able to retrieve drop size distribution parameters of plates and aggregates from spectral radar measurements collected above the melting layer in stratiform precipitation. The drop size distribution parameters are retrieved by fitting the modelled spectral radar observables to the radar measurements using a non-linear least squares optimization technique. This kind of optimization algorithm, changes the dependent variables of the model to obtain the best fit of the model to the measurement.

The retrieval of drop size distribution parameters of plates and aggregates is illustrated on data of stratiform precipitation collected by TARA. TARA is an S-band FM-CW dual polarization Doppler radar, situated at the meteorological site Cabauw, The Netherlands (Russchenberg et al., 2005). Using the outputs of the algorithm, we find that the obtained drop size distribution parameters are consistent. Verification of the outputs of the algorithm is performed by comparison of the estimated ice water content with the liquid water content, obtained below the melting layer. The estimated ice water content is also compared to the measured reflectivity. It is shown that the obtained results for plates are in good agreement with relations between ice water content and reflectivity obtained from literature. A new relation between the ice water content and the reflectivity is derived from aggregates.

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Fig. 1. Typical forms of snow in the different size regions (Magono and Lee 1966).
2 Model: selection of ice particle types

The model is discussed in details in (Spek et al., 2005). The different types of ice particles considered in this model, are drawn in Fig. 1. An outlook of the model is given in Fig. 2. The radar cross section of the different types of particles can be calculated by the model.

Based on the atmospheric conditions above the melting layer during the TARA measurements, columns are probably not present. With the assumption that there is no large updrafts, riming of ice particles is not likely. Considering the high fall velocities of hail and graupel, these types of particles are not present in this measurement of stratiform precipitation. Low mean Doppler velocities and Doppler widths were observed. Finally the possible types of particles left are the aggregates, the plates and the dendrites. In case of a population of plates and dendrites, we assume that the radar backscattering is dominated by plates. The radar cross section of dendrites is smaller than the radar cross section of plates. When dendrites and plates have similar radar cross sections (small diameter), the other microphysical properties (axis ratio,...) are similar and then there is no possibility to differentiate them. The separation between the population of aggregates and plates will be investigated and carried out in this paper using the combination of quasi simultaneous Doppler and polarimetric radar measurements.

3 Retrieval of microphysical parameters

An algorithm is developed here, which extracts microphysical properties of plates and aggregates from spectral radar measurements above the melting layer in stratiform precipitation. The outputs of the model are the spectral equivalent reflectivity (1) and the spectral differential reflectivity (2). These simulated spectra are fitted to the Doppler measurements using a non-linear least squares optimization.

\[
sZ_{hh}(v)dv = \sum_{i=1}^{n_i} N_i(D_i(v)) \sigma_{hi,i}(D_i(v)) \left( \frac{dD_i}{dv} \right) dv
\]

\[
sZ_{dh}(v)dv = \sum_{i=1}^{n_i} N_i(D_i(v)) \sigma_{hi,i}(D_i(v)) \left( \frac{dD_i}{dv} \right) dv
\]

Where \( HH \) and \( VV \) denote respectively horizontal and vertical transmitting and receiving polarization modes of the radar, \( i \) represents the particle type, \( N(D) \) is the exponential drop size distribution, \( v \) is related to the fall velocity \( v_{fall} \) and \( \sigma \) is the radar cross section.

Doppler spectra broadening occurs due to several reasons, such as turbulence, wind, rocking of hydrometeors, etc. On top of that, the ambient wind \( v_0 \) will cause a shift on the fall velocities. Spectral broadening can be modelled as a convolution of the spectral radar observables with a Gaussian convolution kernel. To obtain a realistic model of spectral radar observables, the two parameters \( \sigma_0 \) (width of the broadening Gaussian spectrum) and \( v_0 \), are added to the model. Finally the model of the spectral radar observables depends on 6 parameters:

\[
sZ_{hih}^{mod}(v) = sZ_{hih}^{obs}(v, N_w^{agg}, D_0^{agg}, N_p^{pla}, D_0^{pla}, v_0, \sigma_0)
\]

\[
sZ_{dhi}^{mod}(v) = sZ_{dhi}^{obs}(v, N_w^{agg}, D_0^{agg}, N_p^{pla}, D_0^{pla}, v_0, \sigma_0)
\]

Where \( N_w^{agg}, D_0^{agg} \) and \( N_p^{pla}, D_0^{pla} \) are the intercept parameter [mm m^-3] and the median volume diameter [mm] of the exponential drop size distribution describing, respectively the aggregates and the plates. By changing the
six parameters of the model one by one, whilst keeping the other five parameters constant, a good insight is provided on the dependence of the spectral radar observables on the different parameters of the model. This sensitivity study is reported in (Spek et al., 2005).

From this sensitivity study, the following algorithm is derived. This retrieval algorithm consists of an iterative optimization procedure, which is divided in four stages:

1) Minimization of the cost function, \( L(D_{0}^{agg}, D_{0}^{pla}) \):
\[
\sum_{v} \left[ sZ_{DB}^{\text{meas}}(v) - sZ_{DB}^{\text{mod}}(v, D_{0}^{agg}, D_{0}^{pla}) \right]^2
\] (5)

2) Minimization of the cost function, \( L(\sigma_{0}) \):
\[
\sum_{v} \left[ sZ_{HH}^{\text{meas}}(v) - sZ_{HH}^{\text{mod}}(v, D_{0}^{agg}, D_{0}^{pla}) \right]^2 |_{D_{0}^{agg}, D_{0}^{pla}}
\] (6)

3) Estimation of \( N_{w}^{agg} \) and \( N_{pl}^{agg} \) based on \( sZ_{DB} \) and \( sZ_{HH} \) using the variable projection method (Rust 2003). It allows the derivation of estimates of the intercept parameters without non linear fitting. In stage 4, the ambient wind velocity is the shift between the measured and the modeled spectrum, assuming the other five parameters of the model are known. Summarizing, the six parameters minimization problem can be simplified in a three parameters minimization problem. The quality of the retrieval technique is discussed in (Spek et al., 2005) by using simulations.

4 Application to radar data

The developed retrieval technique is applied to real radar measurements. The data is collected by the radar TARA during a moderate stratiform rain event. The elevation of the radar is 45 deg. The measurements are carried out in alternating polarization mode. The Doppler spectrum is calculated from a time series of 512 samples (2.56 s). Ten Doppler spectra are averaged to obtain the Doppler spectrum, which will be input for the inversion algorithm (25.6 s). The range and the Doppler resolution are respectively 15 m and 1.8 cm s\(^{-1}\).

The measured spectral horizontal reflectivity is shown in Fig. 3. A target approaching the radar has a Doppler velocity negative (convention). The spectral reflectivity is calibrated and its sum over all the Doppler velocities gives the commonly used reflectivity factor. The melting layer is located between 1280 m and 2000 m.

To ensure that there are not rimed particles present, the Doppler spectra used as input for the retrieval algorithm, are selected at least 200 m above the top of the melting layer. Next the inversion algorithm is only applied on the selected spectra when the spectral reflectivity exceeds -10 dB and the maximum spectral differential reflectivity exceeds 0.5 dB. These constraints are necessary to ensure the performance of the retrieval algorithm for plates and aggregates. The chosen Doppler spectra are clipped under 10 dB below the maximum value of the spectral horizontal reflectivity. For spectral reflectivity values under the clipping level, the spectral differential reflectivity is very affected by noise. An example of the selected spectral horizontal and differential reflectivity data with their obtained fits as well as the retrieved six parameters is given in Fig. 4.

Regarding the obtained values of the drop size distributions as well as the retrieved values of spectral broadening and ambient wind velocity, consistency was found for small variations in heights and versus the time (500 s).
4.2 Comparison ice water content with liquid water content

To be able to draw conclusions on the retrieved values, it is necessary to calculate integral parameters, like the ice water content. The ice water content is estimated from the obtained drop size distribution parameters of plates and aggregates using the inversion algorithm. The liquid water content is estimated from the drop size distribution parameters of rain (Moisseev et al, 2006). In Fig. 5, the estimated ice water content and the estimated liquid water content are given as function of time. They show a good agreement, particularly after 250 s. From 0 to 250 s, the ice water content is larger compared to the liquid water content values. It may indicate vaporization of precipitation, which results in a decrease of liquid water content at 950 m where the Doppler spectra, used as input for the inversion algorithm of rain, are selected.

![Fig. 5. Retrieved ice water content and liquid water content versus time.](image)

4.3 Relation between ice water content and reflectivity

There is little knowledge on the microphysical properties of ice crystals above the melting layer of precipitation. In literature, several relations are discussed to obtain ice water content from measured reflectivity values. The goal of the relations is to estimate the vertical structure of the ice water content in clouds. The obtained knowledge is used in climate research and weather forecast (Liu and Illingworth, 2000).

The relation between the ice water content and the equivalent reflectivity at radar frequency of 3 GHz is derived by Hogan et al. (2005):

\[ IWC = 0.02Z_e^{0.66} \]  \[(7)\]

With IWC the ice water content in g m\(^{-3}\) and \(Z_e\) the equivalent reflectivity in mm\(^6\) m\(^{-3}\). This relation is based on measurements of ice particles in non precipitating ice clouds. Using the outputs of the retrieval algorithm, which provides drop size distribution parameters of both plates and aggregates, it is possible to separate the ice water content and equivalent reflectivity values for aggregates and plates. In Fig. 6, the estimated ice water contents are plotted versus the estimated equivalent reflectivities for both plates and aggregates, together with Hogan’s relation. In case of plates, there is a good agreement between the relation provided by Hogan et al. and the results obtained with the inversion algorithm. In case of aggregates the relation between the estimated ice water content and the horizontal reflectivity is obtained by a curve fit:

\[ IWC = 0.0023Z_e^{0.66} \]  \[(8)\]

With IWC the ice water content [g m\(^{-3}\)] and \(Z_e\) the equivalent reflectivity [mm\(^6\) m\(^{-3}\)] of aggregates above the melting layer in stratiform precipitation. The exponent in the estimated ice water content-reflectivity relation (9), is in good agreement with the exponents used in literature. They are generally between 0.55 and 0.74 (Liu and Illingworth, 2000).

![Fig. 6. Estimated ice water content versus estimated reflectivity values for both plates and aggregates.](image)

**References**


Moisseev, D., V. Chandrasekar, C. Unal, and H. Russchenberg, 2006: Dual-polarization spectral analysis for retrieval of effective raindrop shapes. Accepted for publication in *Journal of atmospheric and oceanic technology*.

