HOW DO ICE CRYSTAL HABITS AND SIZE DISTRIBUTION CHARACTERISTICS AFFECT 95 GHZ RADAR SIGNALS?

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1 INTRODUCTION

As the representation of clouds is one of the major uncertainties in general circulation models, information about cloud vertical structure is required for the validation and potential improvement of such models. In recent years, millimeter-wave radars have been proven to be a valuable tool for deducing cirrus cloud macrophysical characteristics such as cloud base and top height as well as numbers of layers. But cloud parametrisations in general circulation models also need microphysical information, like ice water content, crystal size distribution, and crystal shape. Particularly the crystal shape is known to have a strong influence on the radiative properties.

In the following, the potential of ground-based polarimetric cloud radar measurements at 95 GHz (3.16 mm wavelength) to improve information about ice cloud microphysics is evaluated.

The following ice crystal habits and ensemble characteristics may affect the radar signal

- 'effective' particle size
- size distribution type (width/slope)
- particle shape
- particle orientation

The approach is to investigate how variations of these characteristics within their observed range cause changes in the radar signals.

Based on modelling results, the effect of ice crystal habits (shape, size, and orientation) and size distribution characteristics on radar observables as co-polar reflectivity (Z_{hh}), linear depolarization ratio (LDR), and differential reflectivity (Z_{DR}) as well as difference reflectivity (Z_{DP}) are investigated. Technical radar aspects such as scanning capability and cross polarization isolation requirements are assessed.

2 NUMERICAL METHOD

Using the discrete dipole approximation (DDA, see Draine & Flatau, 1994), the backscattering amplitude matrix and thus the single particles radar observables like co-polar reflectivity Z_{hh} and linear depolarisation ratio LDR can be determined for each specified crystal shape, size and orientation (see Lemke & Quante, 1999, for details). Depending on the complexity of the shape, up to 100,000 dipoles are used for representing the particle in the DDA.

Pristine ice crystal shapes are characterised by the aspect ratio *a*, which is the ratio of length to diameter. In the following analysis the aspect ratio is assumed to be size independent. Backscatter intensities have been computed for solid hexagonal columns and plates, hollow cylinders and two types of stellars. A randomly oriented compact column represents a first step towards considering polycrystals at mm-wavelengths, as this compact shape often gives best agreement with measurement, e.g. for near-infrared reflectance (Francis et al., 1998).

Particle sizes are given by the radius *r* of a volume equivalent sphere. Crystal sizes of 0.01 mm to 2 mm in crystal maximum dimension in various orientation scenarios have been modelled. Different size distribution types have been considered representing the same fixed ice water content. The mathematical description of the size distribution of the ensemble is either a modified Γ-function or of power law type

$$N(r) = N_o \cdot r^{\alpha} \cdot \exp(-(3.67+\alpha)\cdot r/r_m) \text{ or}$$
$$N(r) = N^* \cdot r^{\beta}$$

where r_m is the median of the third moment of the distribution. The parameter α controls the width of the distribution, where β gives the slope of the power law curve. N_o / N^* govern the ice water content as integrated quantity. To assess their effect on radar signals, the distribution parameters r_m and α where varied within their reported typical range (Evans & Stephens, 1995).

3 RESULTS FOR REFLECTIVITY

3.1 *Crystals shape*

A relevant question is whether the specific crystal shape has an effect on the observed radar signal. In other words: has the particle shape to be taken into account when modelling the radar signal?

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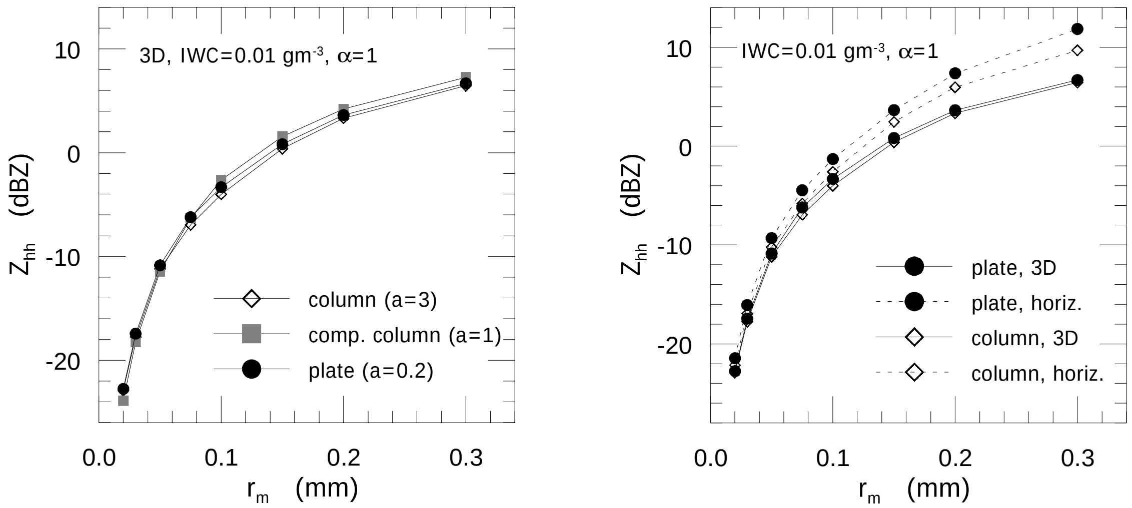
(a) shape (b) orientation



(c) median size & width parameter (d) math. type of size distribution

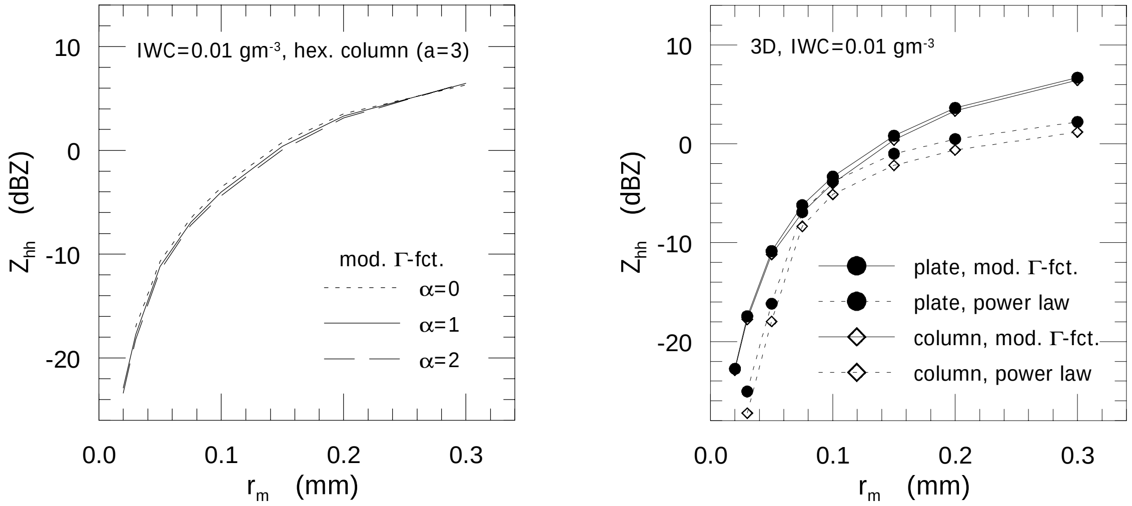


Figure 1: Reflectivity for ensembles of ice crystals as function of the median of the size distribution. The ice water content is fixed to IWC=0.01 gm^{-3} . See text for details.

Figure 1a shows the co-polar reflectivity (Z_{hh}) for ensembles consisting of randomly oriented ice crystals of 3 selected shapes, as function of the median size r_m. The size distribution is represented by a modified Γ-function, where the width parameter is set to $\alpha = 1$. N_o is defined by fixing the ice water content to IWC = 0.01 gm^{-3}, which is a reasonable value for cirrus (Lemke et al., 1997).

While the typical variation of the median particle size causes reflectivity changes of almost 30 dBZ, the effect due to different particle shapes is less pronounced. It should be noted, that this result is strongly dependent on the way particle size is expressed. If taking the particle maximum dimension as reference, the particle shape effect appears more crucial. This is due to the fact that at this wavelength scattering by ice crystals depends more or less on the particle volume. So taking the maximum particle dimension doesn't collect similar volumes and thus introduces an artificial shape dependence.

3.2 *Crystal orientation*

The effect of particle orientation on reflectivity can be estimated from figure 1b, where the reflectivity for ensembles of plates and columns is shown for the two extreme cases of totally random orientation and orientation with major dimension in the horizontal plane. When the median is larger than 0.2 mm, the according reflectivities start to seperate, exhibiting a difference of up to 5 dBZ. Another point is that the shape effect becomes more pronounced than for aligned crystals.

3.3 *Distribution Parameters r_m and α*

Figure 1c is similar to figure 1a but now the particle shape is fixed (hexagonal column) and the distribution width is varied like $\alpha = 0, 1, 2$. Obviously, the variation of distribution width is negligible if compared to the effect due to changes in the median size. Thus, the 2 variable parameters (r_m, α) for describing this type of size distribution can be reduced to 1 (r_m, $\alpha = 1$) within reasonable accuracy.

3.4 *Mathematical type of size distribution*

The results from figure 1c leads to the question, whether the size distribution could be represented by the 'easier' power law. Figure 1d shows the ensemble reflectivity for two particle shapes for both types of size distributions (while IWC is kept constant!).

As the difference accounts to several dBZ, it can be concluded that the explicit shape of the distribution affects the radar signal. The situation may become even more difficult if realistic bi-modal distributions are considered.

4 RESULTS FOR FURTHER OBSERVABLES (POLARIMETRIC OR DOPPLER)

The linear depolarisation ratio (*LDR)* is governed by the crystal shape and much less dependent on size distribution parameters. The effect of particle orientation is almost negligible (not shown). The results indicate that *LDR* is a useful observable for differentiating between the 2 major crystal types namely columnar and planar shapes if one of them is the dominant shape in the radar volume. However, this quantity is difficult to achieve due to technical limits of current systems (Lemke & Quante, 1999).

The differential reflectivity (Z_{DR}) and difference reflectivity (Z_{DP}) involve only co-polar intensities. For an antenna elevation angle of 45°, these parameters are promising for discriminating horizontally aligned pristine crystals from randomly oriented ones or irregular aggregates.

Further improvements in derivation of ice cloud microphysics are expected by incorporating Doppler information from a vertically pointing antenna. For this approach, crystal terminal velocities (v_D) are calculated by using theoretically based power-law expressions predicting fall speeds in terms of ice crystal maximum dimension.

The above results are a first step in the development of retrieval algorithms for a synergy of cloud radar and lidar measurements (Donovan et al., 2001).

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