Revealing Layers of Pristine Oriented Crystals Embedded within Deep Ice Clouds using Differential Reflectivity and the Co-Polar Correlation Coefficient.

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Abstract

Pristine ice crystals typically have high aspect ratios ($\gg 1$), a high density and tend to fall preferentially with their major axis aligned horizontally. Consequently, they can, in certain circumstances, be readily identified by measurements of differential reflectivity (Z_{DR}), which is related to their average aspect ratio. However, because Z_{DR} is reflectivity-weighted, its interpretation becomes ambiguous in the presence of even a few, larger aggregates or irregular polycrystals. An example of this is in mixed-phase regions that are embedded within deeper ice cloud. Currently, our understanding of the microphysical processes within these regions is hindered back by a lack of good observations.

In this paper, a novel technique is presented that removes this ambiguity using measurements from the 3 GHz Chilbolton Advanced Meteorological Radar in Southern England. By combining measurements of Z_{DR} and the co-polar correlation coefficient (ρ_{hv}), we show that it is possible to retrieve both the relative contribution to the radar signal and "intrinsic" Z_{DR} (Z_{DRI}^{P}) of the pristine oriented crystals, even in circumstances where their signal is being masked by the presence of aggregates. Results from two case studies indicate that enhancements in Z_{DR} embedded within deep ice clouds are typically produced by pristine oriented crystals with Z_{DRI}^{P} values between 3 and 7 dB (equivalent to 5—9 dB at horizontal incidence), but with varying contributions to the radar reflectivity. Vertically pointing 35 GHz cloud radar Doppler spectra and in-situ particle images from the FAAM BAe-146 aircraft support the conceptual model used and are consistent with the retrieval interpretation.

1 Introduction

Microphysical processes occurring within mixed-phase clouds dictate the clouds radiative properties [*Comstock et al.*, 2007; *Solomon et al.*, 2007], evolution and lifetime [*Morrison et al.*, 2012], and are fundamental to the production of precipitation [*Mülmenstädt et al.*, 2015]. The effective modelling of these processes depends on accurate representations of the ice crystal scattering properties, fall speeds and primary and secondary ice nucleation mechanisms, which are uncertain [*Harrington et al.*, 1999; *Jiang et al.*, 2000; *Morrison et al.*, 2003]. Complex interactions and feedbacks between incoming and outgoing radiation, cloud dynamics and microphysics make them particularly challenging to understand. Consequently, models struggle to correctly simulate the properties and processes occurring in mixed-phase clouds [*Bodas-Salcedo et al.*, 2008; *Klein et al.*, 2009; *Morrison et al.*, 2009] and they are one of the greatest sources of uncertainty in future climate projections [*Mitchell* *et al.*, 1989; *Sun and Shine*, 1994; *Gregory and Morris*, 1996; *Senior and Mitchell*, 1993]. A key reason for this lack of understanding is a defficiency of good observations and techniques to observe mixed-phase clouds.

In mixed-phase conditions, pristine crystals are known to grow rapidly via the Bergeron-Findeison process; their habit is a function of the environmental temperature and supersaturation in which they form and grow. Their shape determines their scattering properties, growth rate and fall speeds, hence cloud scattering properties, microphysical evolution, precipitation rate and cloud lifetime. Furthermore, estimates of ice water content, or number concentration require accurate knowledge of ice particle shape [*Westbrook and Heymsfield*, 2011]. These pristine crystals typically have a high density, and tend to fall with their major axes aligned horizontally [*Sassen*, 1980; *Cho et al.*, 1981; *Westbrook et al.*, 2010]. This property makes dual polarisation radar a powerful tool for investigating the microphysical properties and processes within mixed-phase clouds, as the preferential alignment of these crystals produces a larger backscatter in the horizontal (H) than the vertical (V) polarisation.

Several studies have noted the existence of strong polarimetric radar signatures embedded within deep ice clouds [*Hall et al.*, 1984; *Wolde and Vali*, 2001; *Hogan et al.*, 2002, 2003a; *Kennedy and Rutledge*, 2011; *Bechini et al.*, 2013; *Andrić et al.*, 2013; *Schrom et al.*, 2015]. *Kennedy and Rutledge* [2011] observed significant increases in the specific differential phase (K_{DP}) embedded in a deep ice cloud at temperatures of about −15°C. By modelling a mixture of aggregates and pristine oriented crystals as oblate spheroids and performing T-matrix scattering calculations, they conclude that this signature was caused by the presence of dendritic particles with diameters of 0.8—1.2 mm with bulk densities greater than 0.3 g cm^{-3}. Similar enhancements of K_{DP} from 27 days of stratiform precipitation using X and C-Band radar measurements were reported by *Bechini et al.* [2013]. They show that for over 70% of cases, the maximum value of K_{DP} above the freezing level was found between -10 and -18°C, and like *Kennedy and Rutledge* [2011] conclude that the enhancement was most likely produced by dendritic crystals. Furthermore, *Bechini et al.* [2013] present evidence that these enhanced K_{DP} signatures aloft are positively correlated with surface precipitation rate in stratiform rainfall, suggesting that this embedded ice growth is important. In combination with generalised multiparticle Mie scattering calculations, *Schrom et al.* [2015] use X-band measurements of Z_H, Z_{DR} and K_{DP} to retrieve particle size distributions of plate and dendritic crystals at around -15°C. However, their method relies heavily on a-priori assumptions about the ice particle size distribution and crystal size-aspect ratio relationships. Using a two-moment bulk microphysical model coupled with electromagnetic scattering calculations, *Andrić et al.* [2013] attempted to reconcile vertical profiles of observed and modelled radar reflectivity (Z_H), differential reflectivity (Z_{DR}), co-polar correlation coefficient (ρ_{hv}) and K_{DP} at S-band. The model microphysics scheme, which included ice crystal nucleation, depositional growth and aggregation, was able to reproduce the shape of the observed profile features, which suggests that vapour deposition and aggregation are able to explain most of the observed radar signatures. However, the magnitudes of the predicted radar variables were not accurately reproduced, implying microphysical processes are either not correctly represented or are missing.

Using the S-band Chilbolton Advanced Meteorological radar situated at the Chilbolton Observatory in Southern England in conjuction with in-situ Johnson-Williams liquid water content measurements from on-board an aircraft, *Hogan et al.* [2002] showed that the presence of elevated Z_{DR} measurements (> 3 dB) embedded within deep ice clouds tended to be associated with supercooled liquid water (SLW), and therefore act as a proxy for mixed-phase conditions. A later study comparing polarimetric radar measurements in deep ice cloud with co-located lidar measurements (which readily detects SLW droplets) from on-board an aircraft confirmed elevated Z_{DR} occurred in regions of SLW [*Hogan et al.*, 2003a].

Z_{DR} is a reflectivity-weighted measure of the aspect ratio of particles within a sample volume. Therefore, it is key for investigating the microphysics of mixed-phase clouds since crystal shape is related to the microphysical processes that formed them and the conditions in which they grow. Unfortunately, the interepretation of Z_{DR} measurements becomes ambiguous when more than once crystal habit is present. The radar signal often becomes dominated by the presence of irregularly shaped polycrystals, or relatively few large aggregates [*Bader et al.*, 1987; *Hogan et al.*, 2002], which have Z_{DR} close to 0 dB, and typically contribute most to the total reflectivity (and hence the overall Z_{DR} of the mixture). This masks the contribution that pristine oriented crystals make to Z_{DR}. *Korolev et al.* [2000] show that in thick stratiform ice cloud, 84% of ice particles > 125 μm are irregularly shaped polycrystals or aggregates [*Stoelinga et al.*, 2007] and that pristine crystals were observed relatively infrequently, and typically embedded within larger zones of these irregularly shaped crystals on scales of approximately 100 m. In order to fully utilise Z_{DR} measurements in deep ice clouds, the masking effect of aggregates must be removed. The aim of this paper is to present a technique that uses the novel combination of Z_{DR} and ρ_{hv} to "unmask" the contribution of pristine oriented ice crystals to the observed radar reflectivity, allowing the information contained within Z_{DR} measurements to be useful even in aggregated regions.

2 Polarimetric radar variables

In this section, the dual polarisation radar variables that will be used extensively in this paper are described.

2.1 Differential reflectivity (Z_{DR})

Differential reflectivity is defined as the ratio of radar reflectivity factors in the horizontal H and V polarisations:

$$Z_{DR} = 10 \log_{10} \left(\frac{Z_H}{Z_V} \right) \quad [\text{dB}] \tag{1}$$

It is therefore a measure of the shape, density and alignment of hydrometeors [*Seliga and Bringi*, 1976]. Positive values occur when the backscatter in the H polarisation is larger than in the V polarisation. This is the case for oblate rain drops or ice crystals aligned with their major axis horizontally aligned. In rainfall, this property can be exploited to improve estimates of rain rate due to the unique relationship between drop size and shape [*Seliga and Bringi*, 1976].

Its interpretation in ice clouds however, is more ambiguous; the shapes and sizes of ice particles are generally not uniquely related. The Z_{DR} of pristine oriented crystals, however, can be readily predicted using Gans theory. Figure 1 shows the Z_{DR} of pristine ice crystals of various axial ratios and air-ice mixtures computed using the modified Gans equations of *Westbrook* [2014]. Due to their high density, pristine crystals aligned with their major axes horizontally can produce very large Z_{DR} signatures. This is particularly true of high-density plates, which can theoretically produce a Z_{DR} measurement up to 10 dB (e.g. *Hogan et al.* [2002]). In any case, the larger the volume fraction of air in these crystals, the lower their "effective" dielectric factor, which is proportional to the bulk density of the air-ice mixture [*Batten*, 1973]. Aggregate crystals consist largely of air and have aspect ratios of only ≈ 0.63 *Westbrook et al.* [2004], therefore produce a low Z_{DR} (typically 0 — 0.3 dB). Since these crystals have a large mass and Z_{DR} is reflectivity-weighted (i.e. effectively mass^2-weighted),

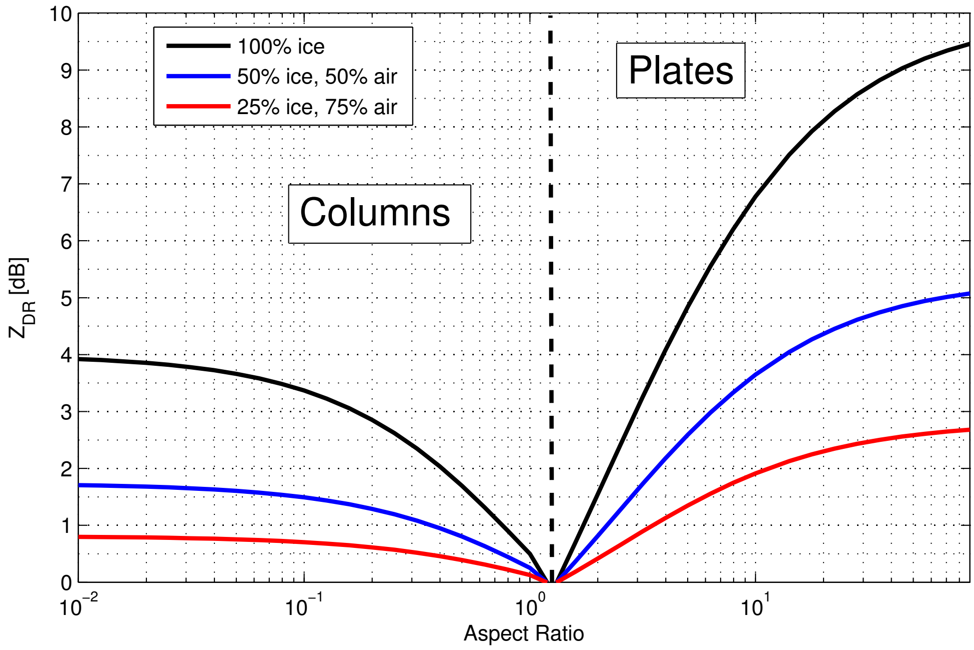

Figure 1. Differential reflectivity of ice particles as function of their aspect ratio. Particles are assumed to be aligned horizontally.

the result is that even a small number of these crystals can dominate the Z_{DR} signal from smaller pristine crystals [*Bader et al.*, 1987].

2.2 The co-polar correlation coefficient (ρ_{hv})

The co-polar correlation coefficient is sensitive to mixtures of particle shapes within a radar sampling volume. It is defined as [*Bringi and Chandrasekar*, 2001]:

$$\rho_{hv} = \frac{\sum S_{HH} S_{VV}}{\sqrt{\sum |S_{HH}|^2 + \sum |S_{VV}|^2}}. \tag{2}$$

where $\sum S_{HH}$ and $\sum S_{VV}$ are the sums of the co-polar elements of the backscattering matrix from each particle in the radar sample volume. It can be estimated by cross correlating successive power or complex (in-phase, I, and quadrature, Q) measurements. ρ_{hv} is a measure of shape diversity within a sample volume. This property makes it complimentary to hydrometeor shape measurements of Z_{DR}. It is has therefore been used to identify the melting layer [*Caylor and Illingworth*, 1989; *Brandes and Ikeda*, 2004; *Tabary et al.*, 2006; *Giangrande et al.*, 2008], ground clutter (e.g. *Tang et al.* [2014]), rain-hail mixtures [*Balakr-*

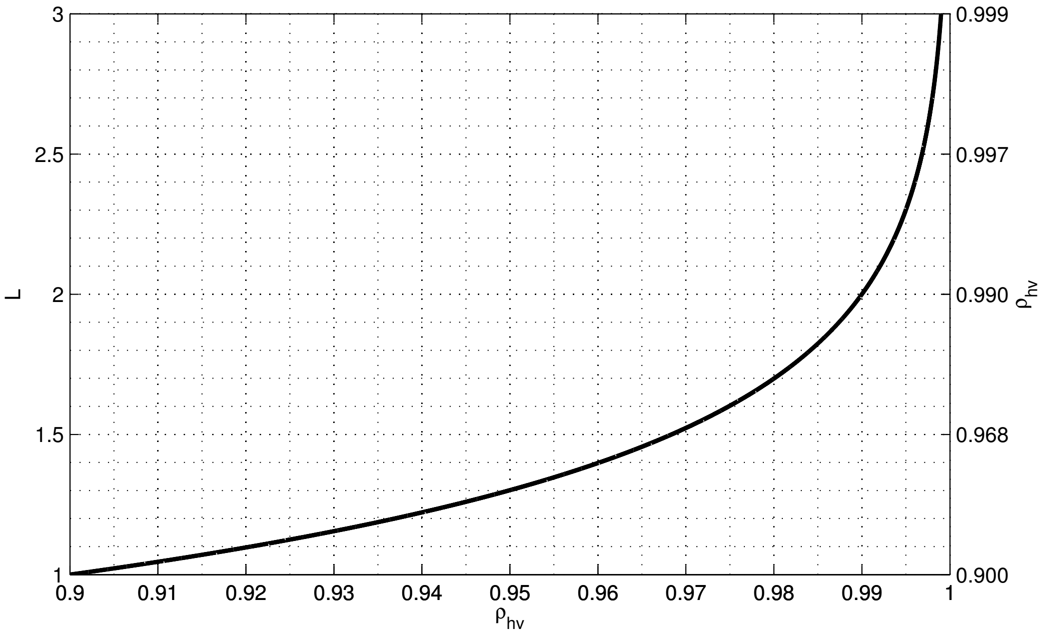

Figure 2. The relationship between $L = -\log_{10}(1 - \rho_{hv})$ and ρ_{hv}.

ishnan and Zrnic, 1990] and interpreting polarimetric signatures in ice (e.g. *Andrić et al.* [2013]), and retrieving the shape of drop size distributions [*Keat et al.*, 2016]. In embedded mixed-phase clouds (containing a mixture of newly formed pristine oriented crystals and aggregates or irregular polycrystals falling from above), one would expect reductions of ρ_{hv} to be co-located with elevated Z_{DR} signatures. Such reductions have been noted [*Moisseev et al.*, 2009; *Andrić et al.*, 2013], but the quantitative microphysical information that is contained within ρ_{hv} is yet to be fully exploited. In order to enable the quantitative use of ρ_{hv}, one must be able to quantify the uncertainty on its measurement. *Keat et al.* [2016] introduce a new variable: $L = -\log_{10}(1 - \rho_{hv})$ which allows rigorous confidence intervals on each ρ_{hv} sample to be derived, using:

$$\sigma_L = \frac{2}{\ln 10} \times \frac{1}{\sqrt{N_{IQ} - 3}} \tag{3}$$

for $N_{IQ} \gg 3$, where N_{IQ} is the number of independent I and Q samples used to calculate each measurement of ρ_{hv}. N_{IQ} can readily be readily estimated using only the observed Doppler spectral width (σ_v):

$$N_{IQ} = \frac{T_{dwell}}{\tau_{IQ}} = \frac{2\sqrt{2\pi}\sigma_v T_{dwell}}{\lambda} \quad (4)$$

where T_{dwell} is the dwell time, τ_{IQ} is the time to independence for I and Q samples, and λ is the radar wavelength.

Furthermore, the Gaussian nature of distributions of this variable prevent the introduction of a bias during averaging many ρ_{hv} samples [*Keat et al.*, 2016]. These statistical advantages mean that the use of L is preferred over ρ_{hv}, and is chosen for use throughout this paper. The relationship between L and ρ_{hv} is shown in figure 2.

3 Retrieval development

In this section, a technique to separate the reflectivity of pristine oriented crystals from co-existing irregular polycrystals or aggregates using polarimetric radar is described. Hereafter, the terms aggregates and polycrystals will be used interchangeably to refer to the pseudo-spherical “background" ice particles that mask the signal from pristine crystals. Fundamentally, the retrieval combines information about the average particle aspect ratio (provided by Z_{DR} measurements), with information regarding the diversity of shapes within a radar sample volume (provided by ρ_{hv}). Qualitatively, if only aggregates are present in a radar sample volume, Z_{DR} would be low (typically 0 — 0.3 dB), and since all particle shapes are the same, ρ_{hv} will be high (close to 1). If only pristine oriented crystals are present, the measured Z_{DR} would be equal to the “intrinsic" Z_{DR} (Z^P_{DRI}) of the pristine oriented crystals, as they are the only crystal habit. For the same reason, ρ_{hv} will again be close to 1. Now, consider the situation where pristine oriented crystals are growing amongst aggregates. The observed Z_{DR} will be related to the reflectivity-weighted aspect ratio of all the particles in the sample volume, and since there is now more than one particle shape, ρ_{hv} will be <1. These situations are summarised in table 1. With some simple assumptions, we will show that each pair of measured ρ_{hv} and Z_{DR} can be uniquely related to the relative contribution pristine oriented crystals make to the observed radar reflectivity compared to aggregates (C) and their Z^P_{DRI}.

The following assumptions are made: (i) Embedded mixed-phase regions consist only of pristine crystals and pseudo-spherical aggregates that can be represented by two distinct ice crystal populations. (ii) The “intrinsic" Z_{DRI} of the aggregates is fixed and assumed to be 0 dB. (iii) Pristine oriented crystals have a fixed aspect ratio, and fall with their major axis

Table 1. Theoretical observations of ρ_{hv} and Z_{DR} for regions of i) Aggregates only, ii) Pristine oriented crystals only, iii) A mixture of pristine oriented crystals and aggregates.

	Expected ρ_{hv}	Expected Z_{DR}
Aggregates only	≈ 1	Z^A_{DRI} (0—0.3 dB)
Pristine crystals only	≈ 1	Z^P_{DRI}
Pristine crystals and aggregates	< 1	$Z^A_{DRI} < Z_{DR} < Z^P_{DRI}$

aligned horizontally. The sensitivity to assumptions (ii) and (iii) are discussed in sections 5.1 and 6.1 respectively.

3.1 Derivation

Under assumption (i), Z_{DR} can be written in terms of the individual radar reflectivity contributions from each crystal type:

$$Z_{DR} = \frac{\sum |S_{HH}|^2}{\sum |S_{VV}|^2} = \frac{Z_H}{Z_V} = \frac{Z^A_H + Z^P_H}{Z^A_V + Z^P_V} \tag{5}$$

where $\sum S_{HH}$ and $\sum S_{VV}$ are the sums of the co-polar elements of the backscattering matrix over all ice crystals. and the superscripts A and P correspond to the aggregate and pristine crystal contributions respectively. Dividing both the numerator and denominator by Z_H, and invoking assumption (ii), $Z^A_H = Z^A_V$:

$$Z_{DR} = \frac{1 + \frac{Z^P_H}{Z^A_H}}{\frac{Z^A_V}{Z^A_H} + \frac{Z^P_V}{Z^A_H}} \tag{6}$$

Under assumption (iii), the “intrinsic" Z_{DR} (the Z_{DR} that would be observed if only the pristine crystals were sampled by the radar) can be defined as:

$$Z^P_{DRI} = \frac{\sum^P |S_{HH}|^2}{\sum^P |S_{VV}|^2} = \frac{Z^P_H}{Z^P_V} \tag{7}$$

By defining the relative contribution of Z_H from the pristine oriented crystals to Z_H of the aggregates as:

$$R = \frac{\sum^{P}|S_{HH}|^2}{\sum^{A}|S_{HH}|^2} = \frac{Z_H^P}{Z_H^A} \tag{8}$$

The observed Z_{DR} of the mixture can be written as:

$$Z_{DR} = \frac{1+C}{1+\frac{C}{Z_{DRI}^P}}. \tag{9}$$

Similarly, for ρ_{hv}, beginning with its definition:

$$\rho_{hv} = \frac{\sum S_{HH}S_{VV}^*}{\sqrt{\sum |S_{HH}|^2 + \sum |S_{VV}|^2}}, \tag{10}$$

and splitting into the contributions from each crystal type:

$$\rho_{hv} = \frac{\sum^{A} S_{HH}S_{VV}^* + \sum^{P} S_{HH}S_{VV}^*}{\sqrt{(\sum^{A}|S_{HH}|^2 + \sum^{P}|S_{HH}|^2)(\sum^{A}|S_{VV}|^2 + \sum^{P}|S_{VV}|^2)}}, \tag{11}$$

Recognising that:

$${S_{VV}^{P}}^2 = \frac{{S_{HH}^{P}}^2}{Z_{DRI}^P}, \tag{12}$$

if aggregates are spherical (assumption ii) and all pristine crystals have a fixed aspect ratio (assumption iii), then:

$$\rho_{hv} = \frac{\sum^{A} {S_{HH}}^2 + \sum^{P} {S_{HH}}^2/\sqrt{Z_{DRI}^P}}{\sqrt{(Z_H^A + Z_H^P)(Z_V^A + Z_V^P)}}. \tag{13}$$

Finally, dividing both the numerator and denominator by Z_H^A yields the observed co-polar correlation coefficient for the mixture:

$$\rho_{hv} = \frac{1+\frac{C}{\sqrt{Z_{DRI}^P}}}{\sqrt{(1+C)\times\left(1+\frac{C}{Z_{DRI}^P}\right)}} \tag{14}$$

The imaginary components of S_{HH} and S_{VV} are ignored in this derivation; absorption is very small at these wavelengths for ice ($\mathrm{Im}(S_{HH}) \ll \mathrm{Re}(S_{HH})$). The two measurements, ρ_{hv} and Z_{DR}, can now be directly related to the two "unknown" parameters, C and Z_{DRI}^P.

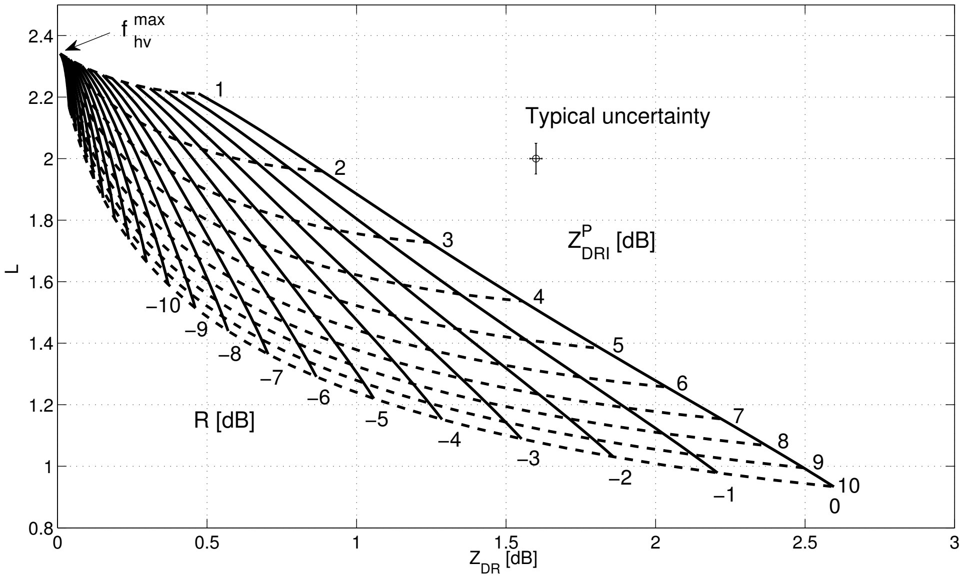

Figure 3. Schematic illustrating predicted C (solid lines) and Z_{DRI}^{P} (dashed lines) as a function of observed L and Z_{DR} based on equations 9 and 14. A representative f_{hv}^{max} (see section 3.2) and typical measurement uncertainty is shown.

Given the preferential statistical characteristics of the variable L over ρ_{hv} [*Keat et al.*, 2016], equations 9 and 14 are used to create look up tables for L and Z_{DR} for C ranging between -20 and 0 dB, and Z_{DRI}^{P} between 0.1 and 10 dB. Figure 3 shows how measurements of L and Z_{DR} are theoretically related to C and Z_{DRI}^{P}. The typical measurement uncertainty on L and Z_{DR} is also shown for data that is presented later. The standard deviation of Z_{DR} ($\sigma_{Z_{DR}}$), was calculated using the method of *Bringi and Chandrasekar* [2001]. Clearly, when C is small, distinguishing between the possible values of C and Z_{DRI}^{P} is difficult, particularly given the magnitude of the measurement uncertainty. However, with increasing C this becomes easier, as the lines of constant C and Z_{DRI}^{P} diverge. The retrieved C and Z_{DRI}^{P} are obtained by minimising the differences between the measured and predicted L and Z_{DR} values in the look-up table, weighted by their measurement uncertainty.

3.2 Practical considerations

When making comparisons between theory and measurements, it is important to account for instrumental and other effects that could be misconstrued as being the result of microphysical changes. Even for a completely mono-disperse particle size distribution and infinite signal-to-noise ratio (SNR), effects such as an imperfect antenna will mean that measurements of ρ_{hv} will always be < 1. Following *Keat et al.* [2016], the maxmimum value that can be measured is referred to as the "inherent limit" of the antenna, f_{hv}^{max}, and can be estimated as the "true" ρ_{hv} value when $Z_{DR} < 0.1$ dB. A representative f_{hv}^{max} of 0.995 ($L = 2.35$) is used to produce figure 3. Predicted L is computed by multiplying ρ_{hv} in equation 14 by f_{hv}^{max}. In order to avoid biases in the retrieval due to poor SNR, look-up tables were created for a range of possible SNR values. The expected ρ_{hv} observation for each C and Z_{DRI}^{P} was adjusted by the factor f, calculated using the following equation from *Bringi et al.* [1983]:

$$f = \frac{1}{\left(1 + \frac{1}{SNR_H}\right)^{\frac{1}{2}} \left(1 + \frac{1}{SNR_V}\right)^{\frac{1}{2}},} \tag{15}$$

These values were then transformed into L space. This allows the retrieval to be applied even when SNR is relatively low (often in lower Z regions of ice cloud). However, doing this has the effect of increasing the impact of measurement uncertainty on retrieved C and Z_{DRI}^{P} uncertainty, as the same uncertainty in L and Z_{DR} now incorporates a larger range of C and Z_{DRI}^{P} values in the adjusted look-up tables. This method of accounting for SNR is preferable to correcting the observed ρ_{hv} value itself for SNR. Data where SNR is < 10 dB is not used in the retrieval.

The retrieval technique also requires accurate calibration of Z_{DR}. This is done regularly (to within ± 0.1 dB) by making measurements of drizzle (low Z), which is known to have a Z_{DR} value of 0 dB.

4 Case study I: 31 January 2014

This section demonstrates the retrieval technique applied measurements made on 31 January 2014. On this day, a warm front passing over the UK was sampled by the dual polarised S-band (3 GHz) Chilbolton Advanced Meteorological Radar (CAMRa), situated in Southern England. This radar boasts a very large antenna (25 m), making it the world's largest fully steerable meteorological radar. The resulting narrow one-way half power beamwidth (0.28°) makes it capable of very high resolution measurements. The radar is a coherent-on-receive magnetron system, transmitting and receiving alternate H and V polarised pulses with a pulse repetition frequency (PRF) of 610 Hz. A cubic polynomial interpolation is used

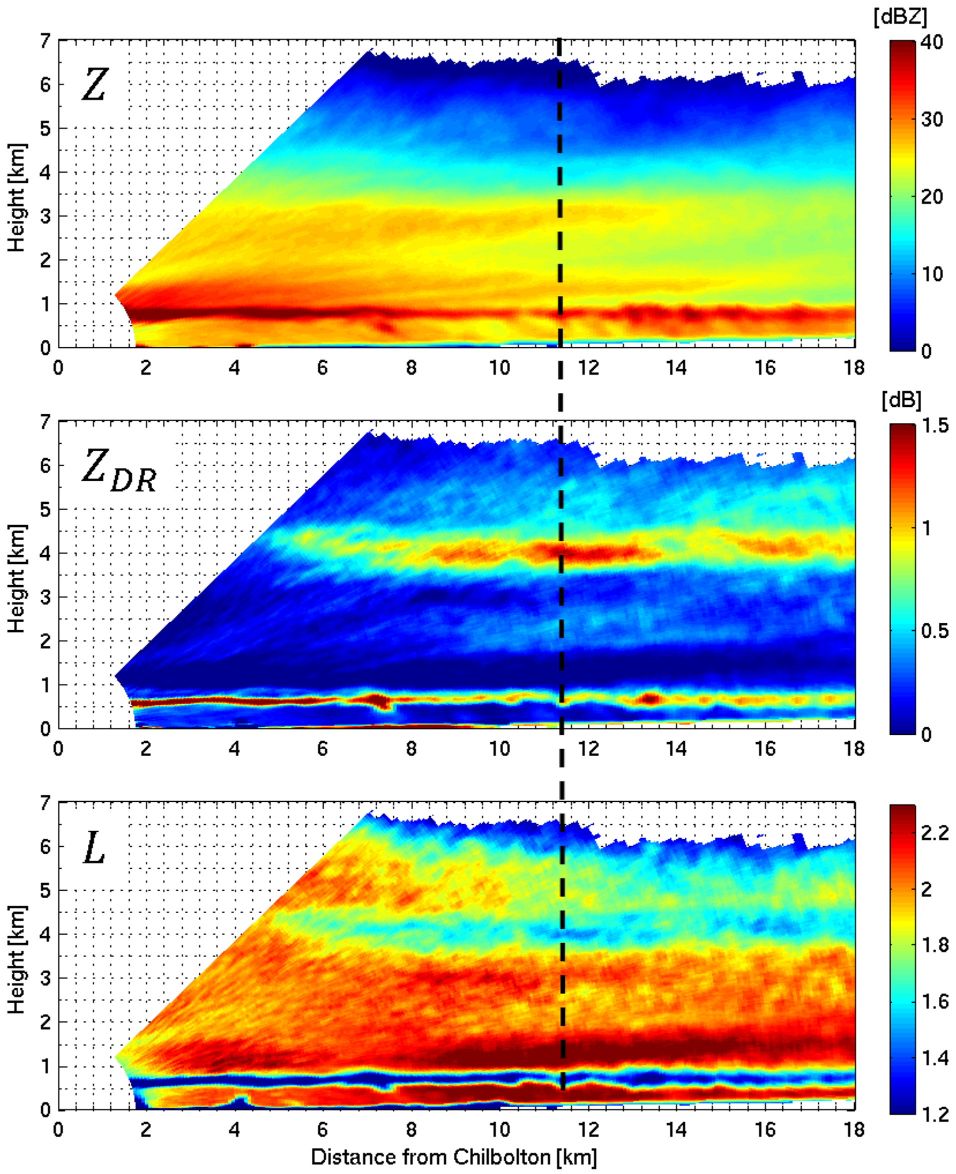

Figure 4. RHI scan at 1501 UTC on 31 January 2014 showing Z, Z_{DR} and L. Data has been averaged to 1° and 300 m in range, and is only shown for SNR > 10 dB. Note that L is the measured values, and significantly affected by low SNR above 4.5 km.

to estimate the H power at the V pulse timing and the V power at the H pulse timing. The sensitivity of the radar is -40 dBZ at 1 km. The full capabilities of this radar are discussed in *Goddard et al.* [1994].

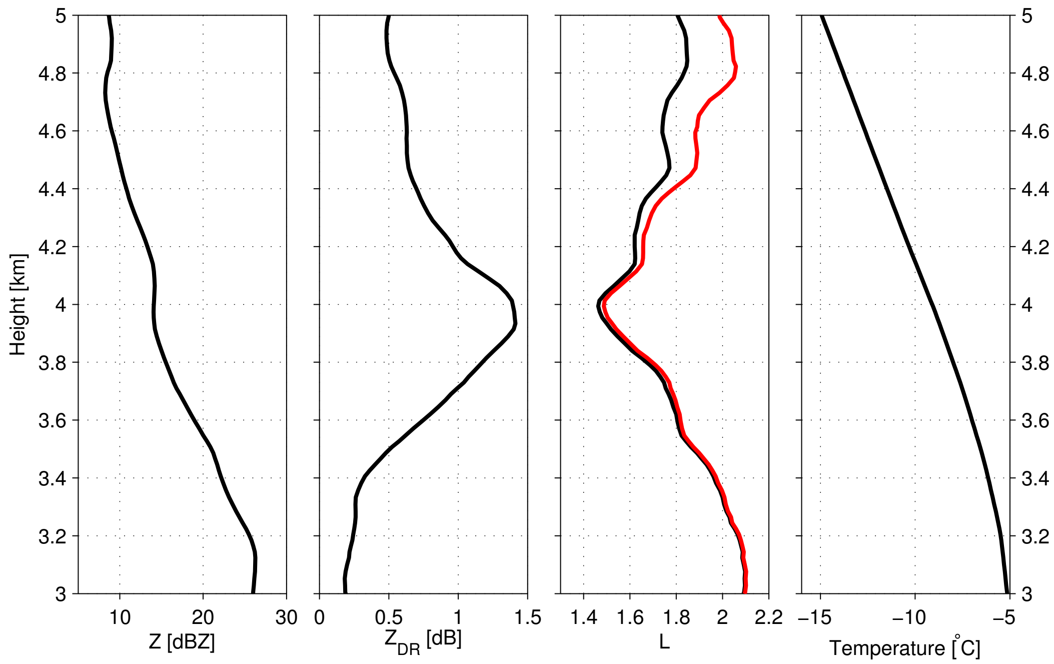

Figure 5. Vertical profiles of Z, Z_{DR}, L and temperature at 11.5 km from Chilbolton at 1501 UTC on 31 January 2014 (indicated by dashed black line on figure 4). The red line is the “effective" L, i.e. the L measurement adjusted for SNR to illustrate the “real" profile used in the retrieval.

Figure 4 shows the observed Z, Z_{DR} and L for a Range Height Indicator (RHI) scan made at 1501 UTC. Data has been averaged over 10 rays (1°) and 4 range gates (300 m) to increase the number of independent I and Q samples and improve the precision of the measurements, and is only shown for SNR $>$ 10 dB. The melting layer can be clearly identified as the thin layer of enhanced Z ($>$ 35 dBZ) at a height of $\approx$ 1 km. Co-located is an elevated Z_{DR} signature, which occurs as ice crystals with positive aspect ratios begin to melt and become water coated, increasing their dielectric factor and therefore radar reflectivity in each polarisation. A decrease in L is also seen due to the mixture of shapes and phases in the melting layer. However, the polarimetric signature of interest can be identified at approximately 4 km in height. Figure 5 shows a vertical profile of Z, Z_{DR}, L and the temperature profile from the operational ECMWF weather forecast model. The location of this profile is indicated by the dashed black line in figure 4. The black line in the L profile shows the measured values of L (influenced by SNR). The red line is L corrected for the effects of SNR using f from section 3.2. This plotted in order to give a sense of the “effective" L that is used in the retrieval once the look-up tables have been adjusted for SNR (as discussed in section

3.2). The profile is only shown between the heights of 3 and 5 km, through the depth of the polarimetric signature of interest. At a height of 5 km, Z is 10 dBZ, whilst Z_{DR} is around 0.5 dB. This is indicative of irregularly shaped polycrystals or pseudo-spherical aggregates. The SNR-adjusted L is 2 (ρ_{hv} = 0.99), indicating that the ice crystals producing this Z_{DR} have approximately the same shape. Descending below 4.8 km, Z and Z_{DR} begin to increase, and L decrease with decreasing height. These trends continue, until at 4 km, Z_{DR} reaches almost 1.5 dB and L reaches a minimum just below 1.5 (ρ_{hv} = 0.97). Interestingly, the L minimum occurs about 50 m higher and is shallower than the Z_{DR} maximum. This feature also appears in vertical profiles presented by *Andrić et al.* [2013].

Our microphysical interpretation of this profile is as follows. Pristine oriented crystals are nucleating at ≈ 4.8 km, presumably in a layer of SLW drops, some of which are nucleated to form new ice particles. The temperature at 4.8 km is ≈ -14°C, meaning these crystals are most likely to be plate-like [*Bailey and Hallett*, 2009]. These plates have positive aspect ratios and fall with their major axis aligned in the horizontal plane. This causes an increase in the reflectivity-weighted aspect ratio (increasing Z_{DR}) and an increase in the diversity of shapes in the sample volume (decreasing L), as they are forming amongst pseudo-spherical aggregate crystals. As these crystals continue to grow by vapour deposition, their contribution to Z increases, Z_{DR} increases, and L decreases, as the reflectivity of the pristine oriented crystals becomes comparable to that of the aggregates (C increases). The peaks in L and Z_{DR} at ≈ 4 km indicate the height at which the process of aggregation begins dominating over the vapour growth of pristine crystals. Between 4 and 3.4 km Z increases by 10 dB, corresponding with a rapid decrease in Z_{DR} to 0.3 dB and increase in L to 2. This is characteristic of aggregation; the particles in the volume are becoming larger and look more spherical to the radar, while overall shape diversity is decreasing. Just before the melting layer is reached, Z_{DR} is very low (≈ 0.2 dB), and L is very high (≈ 2.3), which is indicative of an aggregate-only crystal population.

Figure 6 shows retrieval profiles of C (left) and Z_{DRI}^{P} (right) for the the observations shown in figure 5. The shaded areas depict the uncertainty in the retrieval that results from measurement uncertainty in L and Z_{DR}. This range was calculated as the maximum and minimum possible retrieval values that could result from $L \pm \sigma_L$ and $Z_{DR} \pm \sigma_{Z_{DR}}$.

Firstly, examining the profile between 5 and 4.4 km in height, the retrieval reveals that the observed Z_{DR} of ≈ 0.5 dB is in fact produced by pristine crystals with an intrinsic Z_{DR}

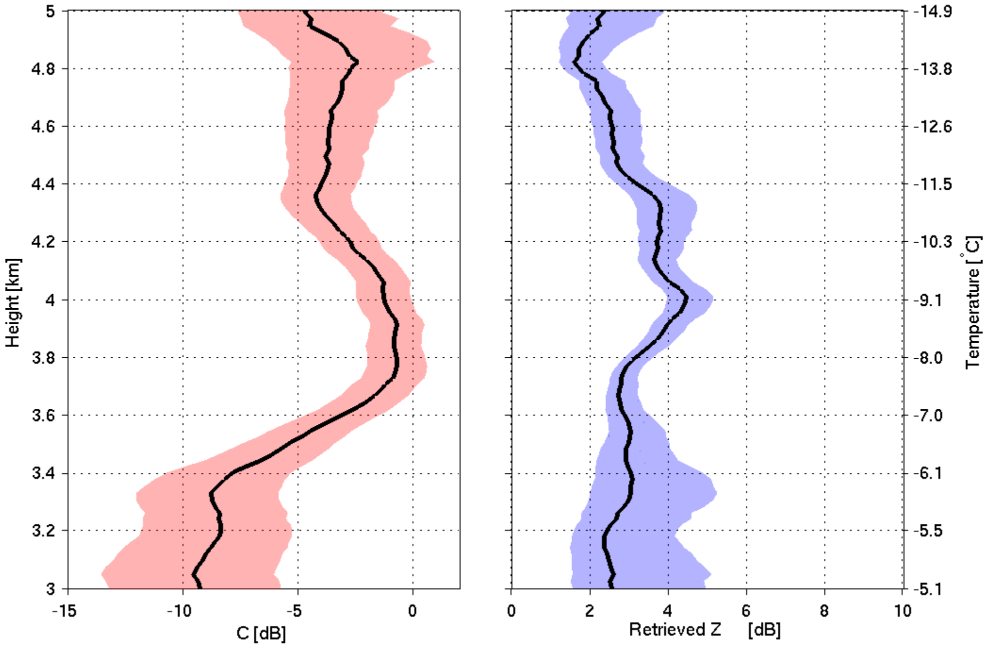

Figure 6. Vertical profile of retrieved C and Z_{DRI}^{P} as a function of height and temperature at 11.5 km from Chilbolton at 1501 UTC on 31 January 2014.

of ≈ 2.5 dB. However, this signal is being masked; the relative contribution of the pristine oriented crystals to the radar reflectivity, C, is ≈ -3 — -4 dB (≈ 40% that of the aggregates). Fluctuations in Z_{DRI}^{P} appear to correspond to a fluctuations in measured L; indeed, inspection of figure 3 reveals that the retrieved Z_{DRI}^{P} value is most influenced by changes along the L axis. Similarly, the relatively steady behaviour of C can be explained by the fact that C is most influenced by changes in the Z_{DR} axis, and Z_{DR} is more smoothly varying. Between 4.4 and 4 km, both C and Z_{DRI}^{P} increase. Plate crystals initially have aspect ratios close to 1:1, which increase as they grow to form thinner structures [*Takahashi et al.*, 1991]. This is consistent with the increase in Z_{DRI}^{P} from ≈ 2 dB at 4.8 km to over 4 dB at 4 km in height. There is then a broad maximum in C between 4 and 3.7 km that corresponds to the location of the strongest Z_{DR} signature. Here, the pristine crystals contribute their highest to the reflectivity; C is ≈ -1 dB (or 80 % that of aggregates). This maximum C value is maintained down to about 3.7 km, whilst Z_{DRI}^{P} decreases back to 3 dB, where it remains approximately constant even as C decreases to -8 dB at 3.4 km. The reduction in C implies that the newly formed crystals are aggregating. This figure demonstrates how the retrieval is able to provide an interpretation of pristine ice crystal properties in deep frontal clouds that was previously unavailable.

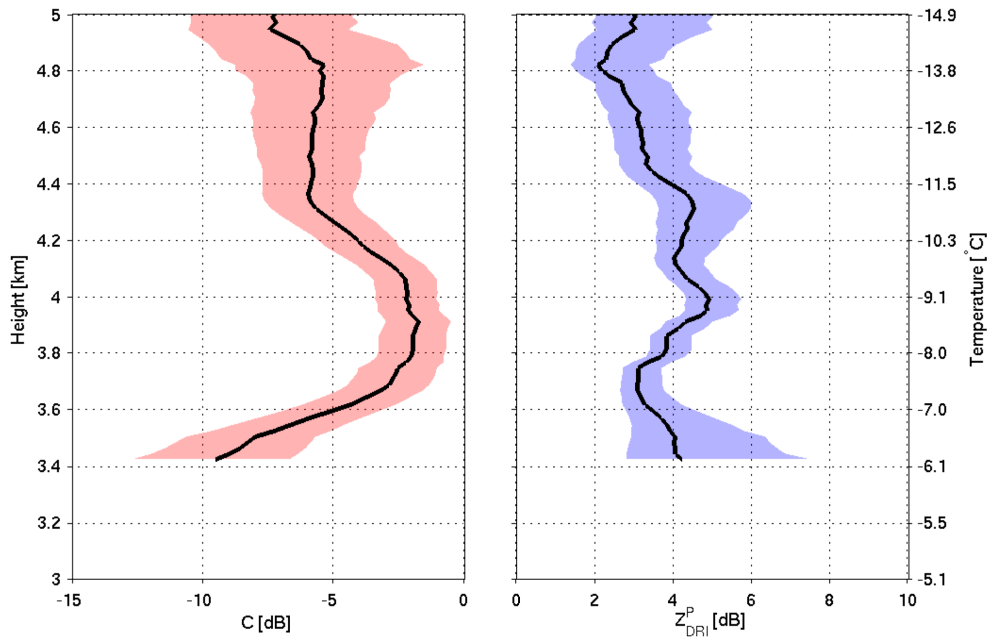

Figure 7. Vertical profile of Retrieved C and Z^P_{DRI} as a function of height and temperature at 11.5 km from Chilbolton at 1501 UTC on 31 January 2014. The retrieval is only shown when C >-10 dB.

5 Accounting for non-spherical aggregates

So far, the retrieval is based on the assumption that aggregates are perfect dielectric spheres to the radar. In nature, this is not necessarily the case; it has been argued in the literature that the mean Z_{DR} of dry and wet aggregates is typically non-zero, but rarely exceeds 0.3 dB [*Ryzhkov and Zrnic*, 1998a; *Ryzhkov et al.*, 2005]. The Z_{DR} of the aggregates just above the melting layer in figure 4) is ≈ 0.2 dB. Assuming aggregates are perfectly spherical rather than slightly non-spherical will result in some of the Z_{DR} signal being mis-attributed to the pristine oriented crystals. It will also cause Z^P_{DRI} to be underestimated; non-spherical aggregates are more similar in shape to pristine oriented crystals.

To account for these non-spherical aggregates, assumption (ii) is relaxed, and a fixed “intrinsic” Z_{DR} of aggregates is assumed, defined as:

$$Z^A_{DRI} = \frac{Z^A_H}{Z^A_V}. \tag{16}$$

To include Z^A_{DRI} as a variable in the retrieval, equation 9 can be slightly modified to:

$$Z_{DR} = \frac{1+C}{\frac{C}{Z^P_{DRI}} + \frac{1}{Z^A_{DRI}}} \tag{17}$$

Similarly, equation 14 can be written as:

$$\rho_{hv} = \frac{\frac{1}{\sqrt{Z^A_{DRI}}} + \frac{C}{\sqrt{Z^P_{DRI}}}}{\sqrt{(1+C)\times\left(\frac{1}{Z^A_{DRI}} + \frac{C}{Z^P_{DRI}}\right)}} \tag{18}$$

Figure 7 shows the same profiles as figure 6 but with an assumed Z^A_{DRI} of 0.3 dB. Broadly, the profile characteristics remain similar to the case when Z^A_{DRI} = 0 dB. Retrieved quantities are only shown where the polarimetric signature is strong enough to produce $C >$ -10 dB, and the retrieval is deemed reliable. The two local maxima in Z^P_{DRI} are observed at the same heights, and the broad maximum in C is still present between 4.4 and 3.5 km. However, the magnitudes of the retrieved quantities are different. C has typically decreased at all heights, whereas Z^P_{DRI} has typically increased. The peak in C is now ≈ -3 dB not -1 dB, and typically Z^P_{DRI} values are now 5 rather than 3—4 dB. The retrieval uncertainty is also slightly larger, because the adjustment for Z^A_{DRI} puts the observed L and Z_{DR} into the more sensitive part of the forward model. This causes the same measurement uncertainty to span over a larger range of possible C and Z^P_{DRI} values. The precise magnitudes of these changes depend on the sensitivity of the forward model for each particular pair of L and Z_{DR} observations. This will be quantified in section 5.1.

5.1 Sensitivity to the assumed Z_{DR} of aggregates

In this section, we investigate the sensitivity of the retrieval to the assumption of aggregate Z_{DR}. L and Z_{DR} were forward modelled using Z^A_{DRI} assumptions of 0 and 0.3 dB, covering the expected Z_{DR} range for aggregates. The sensitivity of the forward model is defined here as the absolute difference in retrieved C and Z^P_{DRI} due to Z^A_{DRI} changing between these limits, for a given pair of L and Z_{DR} observations. The uncertainty in L and Z_{DR} is set to 0.05 and 0.02 dB respectively, which is typical for the data used in the retrievals. Figure 8 shows the sensitivity of C (top) and Z^P_{DRI} (bottom) to this difference. Both C and Z^P_{DRI} are increasingly sensitive for higher L and lower Z_{DR}. This is not surprising, as the measured polarimetric signature here is weaker, and C and Z^P_{DRI} lines are almost indistinguishable (see figure 3). It is clear that C is most sensitive to the choice of Z^A_{DRI}, exhibiting sensitivity ≳

2.5 dB up to Z_{DR} = 1 dB. This sensitivity decreases as Z_{DR} increases; for Z_{DR} = 1.5 dB (the upper range of the data presented here), the sensitivity is 1 — 2 dB.

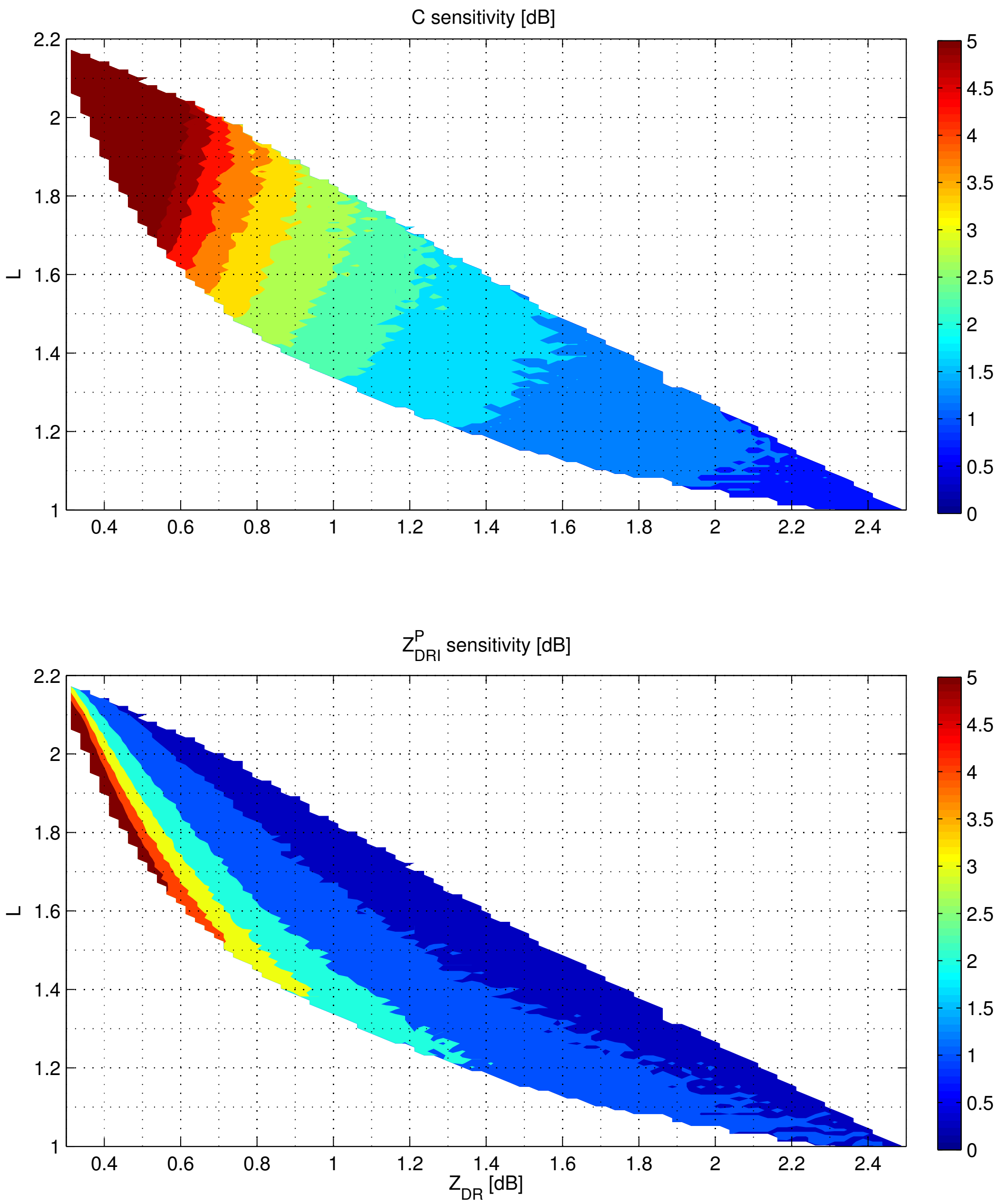

Figure 8. The sensitivity of retrieved C and Z^{P}_{DRI} to the assumption of Z^{A}_{DRI}, expressed as the difference between assuming Z^{A}_{DRI} = 0.3 dB as opposed to 0 dB.

The retrieved Z^{P}_{DRI} is also sensitive to the choice of Z^{A}_{DRI}, especially for low L (i.e. where retrieved Z^{P}_{DRI} values are highest). Above Z_{DR} = 1 dB, the sensitivity is typically

1—2 dB. Clearly, care should be taken when interpreting the retrieval results for weak polarimetric signatures.

6 Accounting for pristine oriented crystal aspect ratio variability

Another assumption made in the retrieval is that all of the pristine oriented crystals have a fixed aspect ratio. In reality, ice crystals are nucleated at different depths within a SLW layer and can grow at different rates, leading to an eventual distribution of aspect ratios for a given crystal habit. Not accounting for a variety of crystal aspect ratios will cause the retrieved Z_{DRI}^{P} for a given L measurement to be overestimated. This is because the measured L will include a contribution from pristine crystal shape diversity which would be misinterpreted as being the result of pristine crystals with more extreme aspect ratios. It would also cause C to be underestimated for a given Z_{DR} measurement.

The forward modelled Z_{DR} values will not be affected by an increase in shape variety, as in what follows uniform distributions are defined about the mean Z_{DRI}^{P} value, such that the average Z_{DRI}^{P} remains the same. Therefore, Z_{DR} can be predicted using an equation identical to 9, but where Z_{DRI}^{P} should be interpreted as the the reflectivity-weighted average of the Z_{DRI}^{P} distribution. The predicted L observation will be affected, as it is sensitive to any additional variability in shape. To account for this, an equation can be derived similarly to equation 14, using the definitions of C and Z_{DRI}^{P} given by equations 7 and 8.

Starting with the definition of ρ_{hv}, and separating into the contributions from each crystal type:

$$\rho_{hv} = \frac{\sum^{A} S_{HH}S_{VV} + \sum^{P} S_{HH}S_{VV}}{\sqrt{(\sum^{A}|S_{HH}|^2 + \sum^{P}|S_{HH}|^2)(\sum^{A}|S_{VV}|^2 + \sum^{P}|S_{VV}|^2)}} \tag{19}$$

Dividing both the numerator and denominator by Z_H^A, and assuming initially that aggregates are spherical ($S_{HH} = S_{VV}$):

$$\rho_{hv} = \frac{1 + \frac{\sum^{P} S_{HH}S_{VV}}{Z_H^A}}{\sqrt{\left(1 + \frac{Z_H^P}{Z_H^A}\right)\left(\frac{Z_H^P}{Z_H^A} + \frac{Z_H^P}{Z_H^A}\right)}} \tag{20}$$

Noting that in the numerator,

$$\frac{\sum^P S_{HH}S_{VV}}{Z_H^A} = \frac{Z_H^P}{Z_H^P} \times \frac{\sum^P S_{HH}S_{VV}}{Z_H^A} = C \times \frac{\sum^P S_{HH}S_{VV}}{Z_H^P}, \tag{21}$$

$$C \times \frac{\sum^P S_{HH}S_{VV}}{Z_H^P} = C \times \frac{\sum^P S_{HH}S_{VV}}{\sqrt{\sum^P |S_{HH}|^2 \sum^P |S_{VV}|^2}} \times \sqrt{\frac{\sum^P |S_{VV}|^2}{\sum^P |S_{HH}|^2}}$$

$$= C \times \rho_{hv}^P \times \sqrt{\frac{1}{Z_{DRI}^P}}, \tag{22}$$

then:

$$\rho_{hv} = \frac{1 + C \times \rho_{hv}^P \times \sqrt{\frac{1}{Z_{DRI}^P}}}{\sqrt{\left(1 + \frac{Z_H^P}{Z_H^A}\right)\left(\frac{Z_H^P}{Z_H^A} + \frac{Z_H^P}{Z_H^A}\right)}} \tag{23}$$

where ρ_{hv}^P is the co-polar correlation coefficient that would result from a mixture of pristine crystals in the absence of any aggregates, characterising the shape diversity of the pristine crystal population. Therefore:

$$\rho_{hv} = \frac{1 + C \times \rho_{hv}^P \times \sqrt{\frac{1}{Z_{DRI}^P}}}{\sqrt{(1 + C) \times \left(1 + \frac{C}{Z_{DRI}^P}\right)}} \tag{24}$$

Note that this equation can be readily modified to include the effect of an arbitrary intrinsic differential reflectivity Z_{DRI}^A, similar to the approach in section 5.1:

$$\rho_{hv} = \frac{\frac{1}{\sqrt{Z_{DRI}^A}} + C \times \rho_{hv}^P \times \sqrt{\frac{1}{Z_{DRI}^P}}}{\sqrt{(1 + C) \times \left(\frac{1}{Z_{DRI}^A} + \frac{C}{Z_{DRI}^P}\right)}} \tag{25}$$

6.1 Sensitivity to fixed aspect ratio assumption

The sensitivity of the retrieval to the assumption of a fixed aspect ratio is tested using the same method as that used to test the sensitivity to the assumption of Z_{DRI}^A. L and Z_{DR} were forward modelled, but for each Z_{DRI}^P value, a uniform distribution of Z_{DRI}^P with a width of 1 dB was assumed. Figure 9 shows the sensitivity of C (top) and Z_{DRI}^P (bottom) to assuming a uniform 1 dB distribution width compared to a fixed aspect ratio.

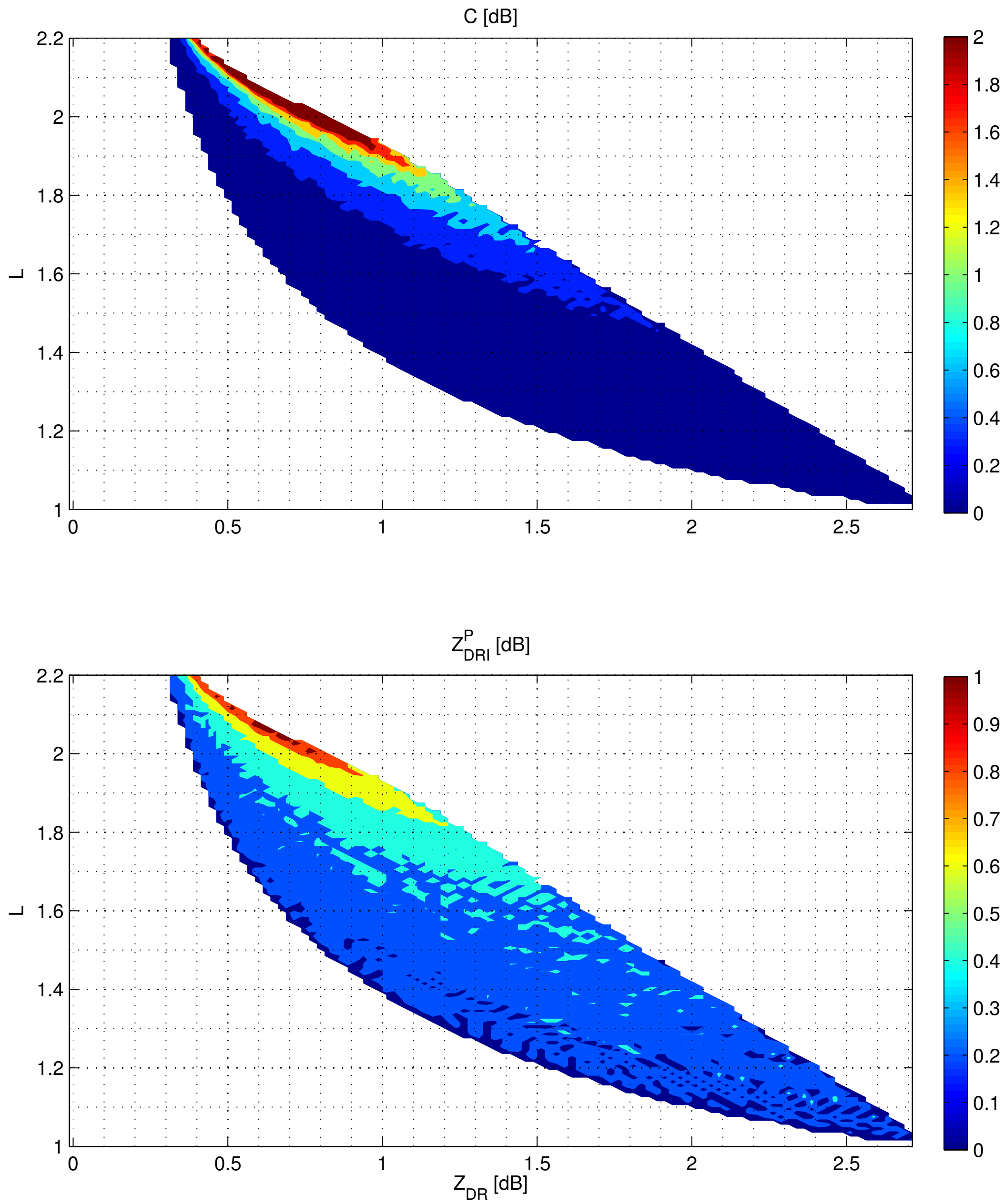

Figure 9. The sensitivity of retrieved C and Z^P_{DRI} to assuming a uniform Z^P_{DRI} distribution width of 1 dB compared to assuming a fixed aspect ratio.

Clearly, C and Z^P_{DRI} are much less sensitive to the assumption of a fixed aspect ratio than they are to the assumption of Z^A_{DRI}. The greatest sensitivity in both C and Z^P_{DRI} again occurs when the polarimetric signal is relatively weak ($L > 1.8$ and $Z_{DR} < 1$ dB). There is pronounced sensitivity to a distribution of pristine oriented crystal shapes for higher L (which corresponds to smaller predicted Z^P_{DRI} values). This is because the contribution to the reduction of L caused by pristine oriented crystal aspect ratio variability (ρ^P_{hv} in equation 23) is larger when the Z^P_{DRI} distribution width is comparable in magnitude to the mean Z^P_{DRI} value. Again, the retrieved C is most sensitive to the assumption. For high L and low Z_{DR}, it is as large as 2 dB, but, for the majority of L and Z_{DR} values the sensitivity is lower than 0.5 dB. Z^P_{DRI} is less sensitive overall, and broadly less than 0.5 dB. The retrieval is therefore considered to be insensitive to pristine crystal shape variability, except for when the polarimetric signature is very weak.

7 Case study II: 17 February 2016 — Concident radar and in-situ observations

On February 17 2016, an occluded front stalled over the UK, producing precipitation over Chilbolton that lasted almost 12 hours. In addition to making polarimetric radar measurements of the deep ice cloud on this day with CAMRa, the Facility for Airborne Atmospheric Measurements (FAAM) BAe-146 aircraft also made in-situ measurements. Furthermore, Doppler spectra were also measured from the vertically pointing Copernicus 35 GHz Doppler radar, also situated at the Chilbolton Observatory.

Figure 10 shows the observed Z, Z_{DR} and L for an example RHI scan taken at 1156 UTC. The melting layer can again be clearly identified by the enhanced Z, Z_{DR} and decreased L at approximately 500 m in height. As in Case I, a polarimetric signature of enhanced Z_{DR} and decreased L is seen at approximately 4 km in height. However the increase in Z and Z_{DR} and reduction in L are weaker in this case study. Figure 11 shows the observed profiles of Z, Z_{DR}, observed and "effective" L at a range of 8.5 km from Chilbolton (black dashed line in figure 10). We can see that Z_{DR} reaches only ≈ 1 dB, and minimum L is ≈ 1.7. L is lower towards the cloud top than in case study I, as the SNR is lower. Evidence of further pristine ice crystal formation and growth is indicated by enhanced Z_{DR} between 2 and 3 km, and an increase in Z. Unfortunately, the strength of this secondary signature is insufficient for a reliable retrieval. It is interesting to note that there appeared to be evidence of ice production at this height in vertically pointing radar Doppler spectra (this is discussed in more detail in section 7.2). A similar feature is also present in the January 31 2014 case study.

The interpretation of these profiles is broadly similar to that of case study I. At 4.6 km, the temperature is ≈ -15°C; Z is ≈ 7 dBZ, Z_{DR} is ≈ 0.4 dB and L is ≈ 1.9; this is consistent with a monodisperse population of small, irregular polycrystals or aggregates. Below, L de-

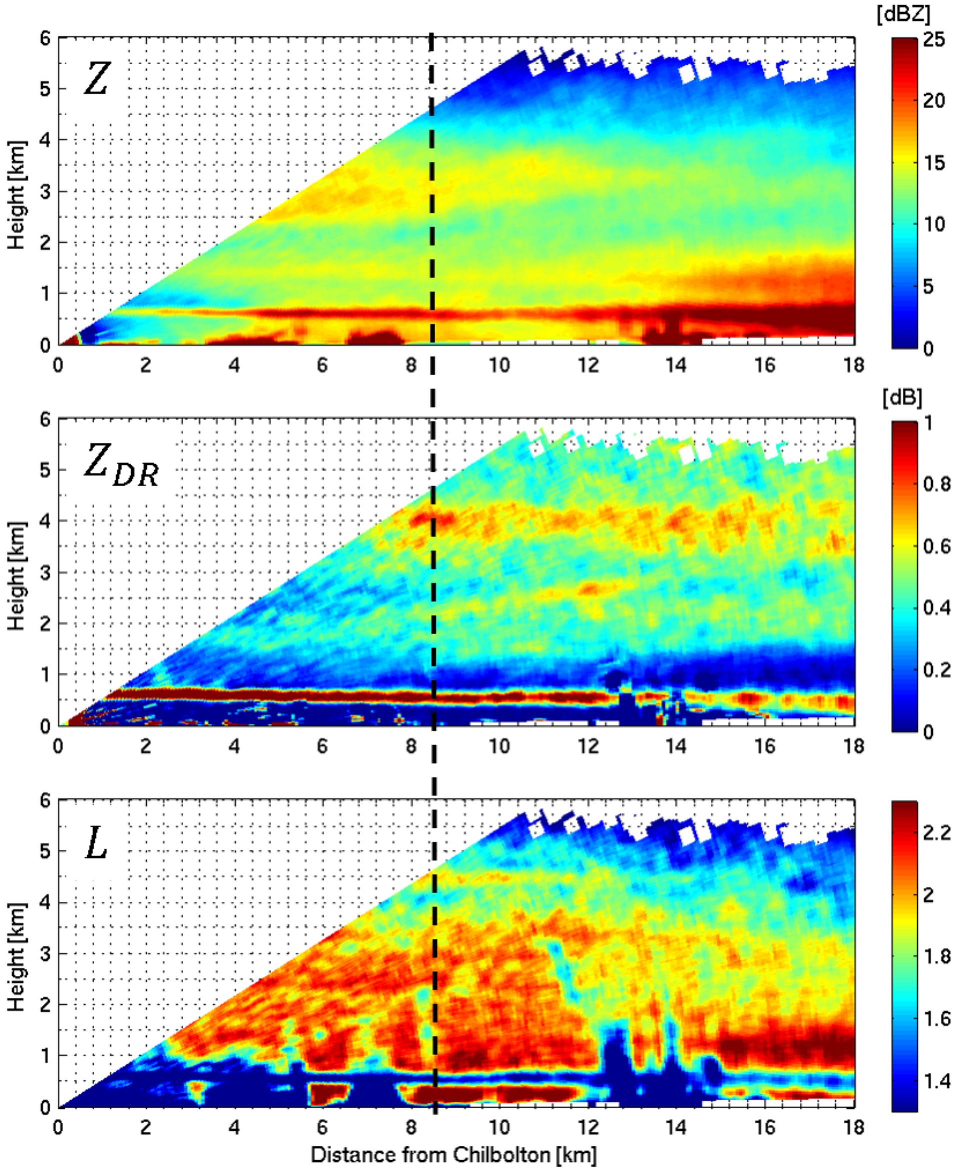

Figure 10. RHI scans of Z, Z_{DR}. and L at 1156 UTC on 17 February 2016. Data has been averaged to 1° and 300 m in range, and is only shown for SNR > 10 dB. Areas of low L (up to a height of 2 km between 12 and 15 km in range) is the result of ground clutter; the signature of interest is located at ≈ 4 km.

creases to ≈ 1.7 at 4.1 km, whilst Z_{DR} increases to a peak of 0.8 dB at 4 km. Like Case I, the minimum in L appears to be slightly higher in altitude than the peak in Z_{DR}. Below 4 km, Z_{DR} decreases, whilst L increases, indicative of aggregation. Sharp gradients in Z_{DR} and L at 3.2 km (-7°C) and a corresponding increase in Z also seem to suggest rapid aggregation of the pristine crystals.

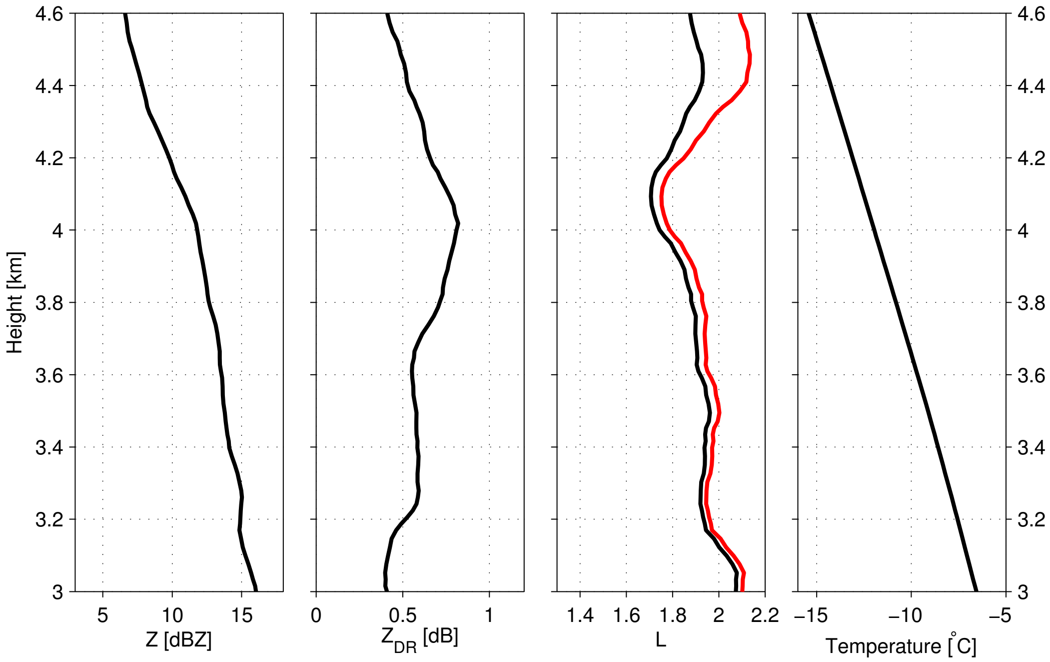

Figure 11. Vertical profiles of Z, Z_{DR}, L and temperature at 8.5 km in range at 1156 UTC on 17 Feb 2016 (indicated by dashed black line on figure 10). The red line is L adjusted for SNR effects.

7.1 Retrieval profiles

As before, C and Z_{DRI}^{P} are retrieved using look-up tables based on equations 18 and 17 (including a Z_{DRI}^{A} of 0.15 dB and assuming a fixed pristine oriented crystal aspect ratio). The results are shown in figure 12. At a height of 4.4 km, C is ≈ -5 dB. After decreasing slightly, it gradually increases until a maximum of -4 dB is reached at a height of 3.9 km. Meanwhile, Z_{DRI}^{P} gradually increases from 2 dB to its maximum of ≈ 4 dB at 4.1 km, approximately 200 m higher than the peak in C. From there, Z_{DRI}^{P} decreases to ≈ 3 dB at the location of maximum C (3.9 km), where it remains down to 3.2 km. Microphysically, the these profiles can again be explained by plate-like crystals nucleating at ≈ -14°C, and growing by vapour deposition, eventually aggregating below. As in Case I, the peak in Z_{DRI}^{P} is not co-located with peaks in C, but seem to occur above them. For plate-like crystals growing by vapour deposition, it might be expected that they should be co-located, as crystals with larger aspect ratios will both contribute more to Z_H and increase their Z_{DRI}. However, Z_{DRI}^{P} is also dependent on the effective particle density. We speculate that the peaking of Z_{DRI}^{P} above the location of peak C occurs because the plates growing rapidly by vapour deposition are initially of high density. The subsequent decrease in Z_{DRI}^{P} during elevated C is indicative of lower density pristine crystals, such as plates with extensions or dendrites. Aircraft imagery shown in section 7.3 support this interpretation.

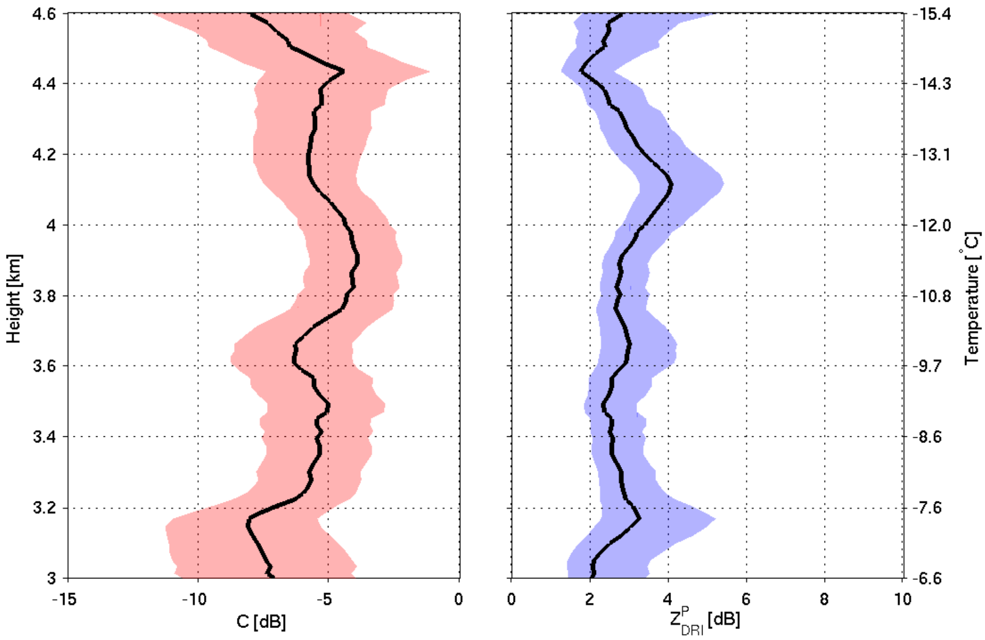

Figure 12. Vertical profile of retrieved C and Z^P_{DRI} as a function of height and temperature at 8.5 km from Chilbolton on 17 February 2016.

7.2 Coincident Doppler spectra

In addition to the polarimetric information collected from CAMRa, the 35 GHz Copernicus Doppler radar also situated at the Chilbolton Observatory was operating at zenith during this case study, measuring full Doppler spectra. Figure 13 shows an example spectograph from 1238 UTC. Power is integrated over 10 s for height bins of 30 m. At 7.5 km in height, a single, narrow peak in backscattered power is measured, corresponding to Doppler velocities between 0.5 — 0.6 ms^{-1}. This indicates that hydrometeors producing this backscatter are relatively small, and are all falling at approximately the same speed. At $\approx$ 5.5 km, both magnitude of the backscattered powers and width of the power spectra increase, indicating that there is an increase in the number and/or size of the ice particles, and a greater spread in their fall speeds. The peak power corresponds to fall speeds of $\approx$ 1 ms^{-1}. This trend of increasing power and corresponding Doppler velocity continues, which is indicative of these ice crystals growing larger by aggregation. The fluctuation in the power spectra at approximately 1.5 km is likely to be the result of turbulence; observed Doppler velocities also contain contributions from ambient air motions within the cloud. No attempt to correct for these motions has been made.

There are a number of fascinating signatures in this spectrograph. Of primary interest in this paper is the bi-modality observed between 3.5 and 4.5 km (indicated by the box in figure 13), which suggests that at this height there are two distinct ice populations: newly formed pristine crystals (falling slowly) and aggregates or polycrystals (falling more quickly). This feature is observed at the same height as the enhanced polarimetric signatures observed by CAMRa (figure 10), supporting the interpretation of the retrieval that pristine oriented crystals with large aspect ratios are growing rapidly at these heights by vapour deposition. Their consequent growth by vapour deposition (increase in mass) is illustrated by the gradual increase in the power and the Doppler velocity down to a height 3.5 km, below which the crystals have become large enough and/or have aggregated so that their fall speeds are comparable to the aggregates, and the spectrum once again becomes monomodal. However, there is evidence of slight bi-modality even down to 2.5 km, which would be consistent with elevated Z_{DR} signature observed here by CAMRa. Further bi-modality in the Doppler spectra can be observed between 1.5 and 2.5 km in height.

The bi-modality of the spectra between 3.5 and 4.5 km in height provide an opportunity to independently estimate the contribution of the pristine crystals to the radar reflectivity, using a similar method to that used by *Rambukkange et al.* [2011]. The contributions to backscattered power from each ice crystal population were separated using Doppler velocity thresholds. For each crystal type, the radar reflectivity was calculated by integrating the power spectra over velocity ranges of 0—0.4 ms^{-1} at 4.3 km to 0—0.8 ms^{-1} at 3.4 km, the range increasing to ensure that the power backscattered from increasingly faster falling pristine crystals remained separated from the aggregates. Figure 14 (a) to (c) show the observed power spectrum (and 11^{th} order polynomial fits) at heights of 4.3, 4.1 and 3.8 km respectively. At 4.3 km, not long after the ice crystals have been nucleated, there is a very clear bi-modal power spectrum. By 4.1 km, the pristine oriented crystals have grown larger (indicated by their larger fall speeds), but their peak is still clearly distinguishable from the aggregates. By 3.8 km, the pristine crystals are almost falling at the same rate, leading to an almost monomodal distribution. Figure 14 (d) shows C as a function of height estimated using this Doppler spectral method. Qualitatively, C estimated with this method behaves very similarly to C retrieved using the polarimetric retrieval. The broad maximum in C is reproduced at the correct heights, providing evidence that the newly developed polarimetric

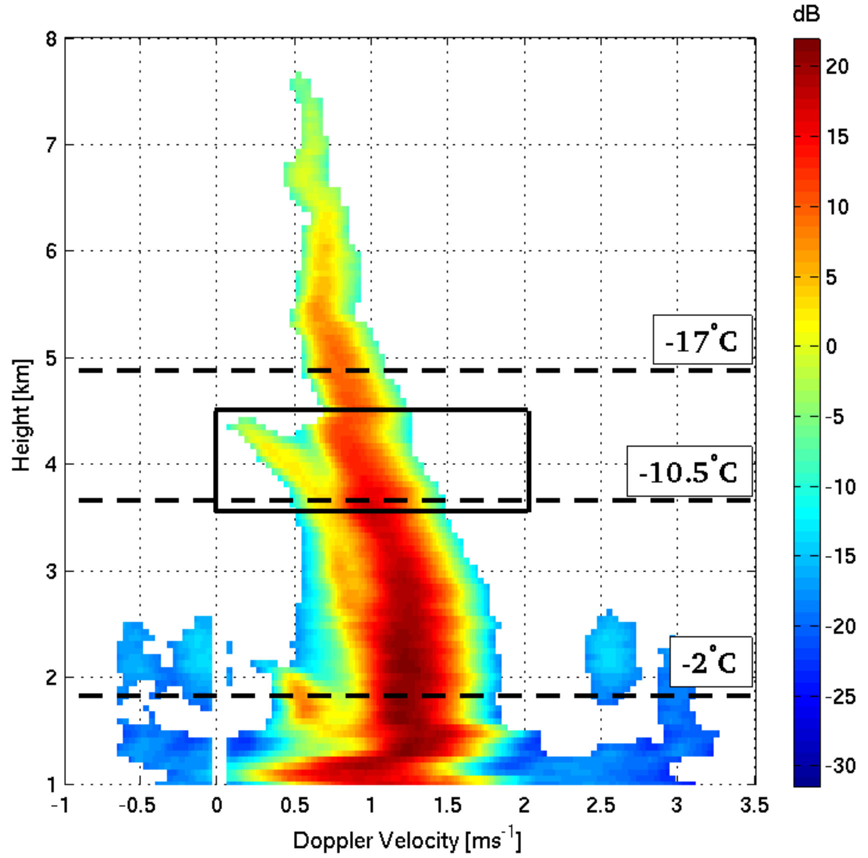

Figure 13. Doppler spectra from the 35 GHz radar at 1238 UTC on Feb 17th 2016. The box indicates the primary signature of interest. The dashed lines correspond to the flight altitudes of the FAAM BAe-146 aircraft.

retrieval technique is capturing the presence and growth pristine oriented crystals at these heights. The magnitude of C is lower compared to the polarimetric retrieval, however, direct quantitative comparison is not meaningful because the profiles are separated in space by 8.5 km.

7.3 In-situ aircraft measurements

Between 1200—14000 UTC, the FAAM BAe-146 aircraft, equipped with an array of cloud microphysical probes, made a series of flight runs at temperatures of microphysical interest. The altitudes of these flight runs are indicated by the dashed lines in figure 13. The quasi-stationary nature of this front means that, although these measurements were sepa-

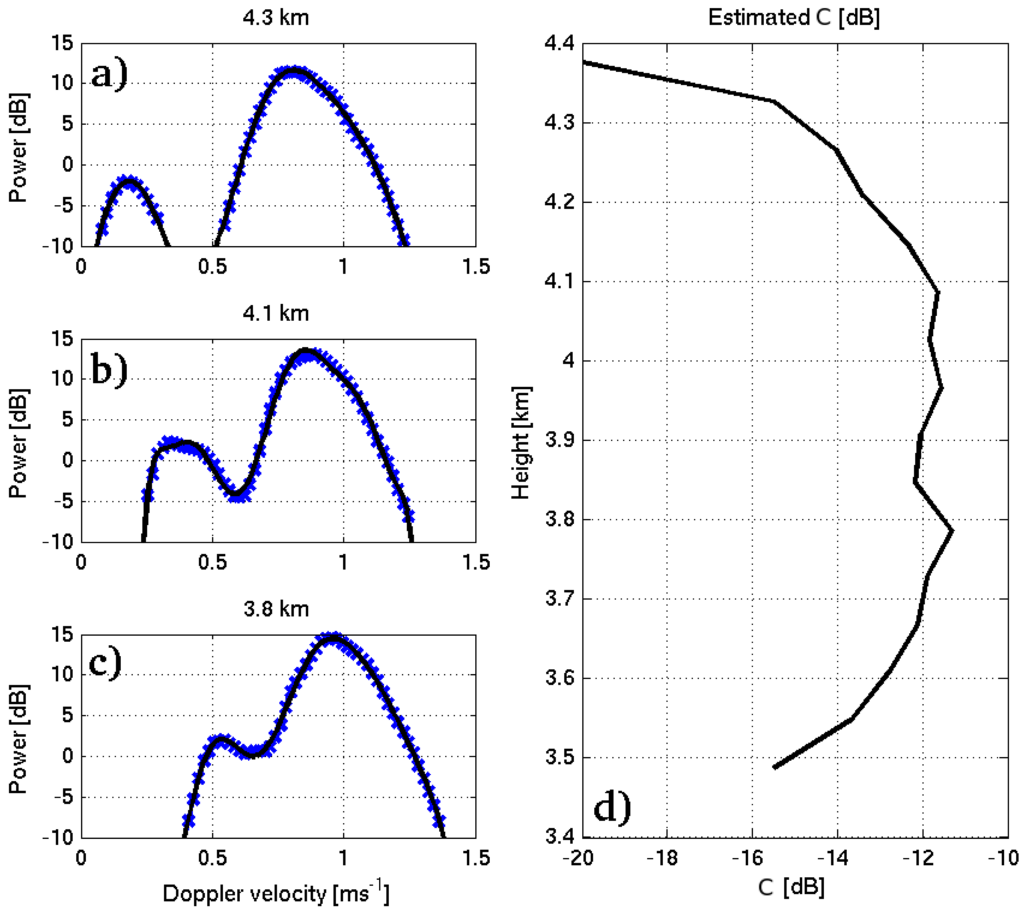

Figure 14. Power distributions at heights of (a) 4.3 km, (b) 4.1 km and (c) 3.8 km from the Doppler spectra in figure 13. (d) shows *C* estimated from these power spectra.

rated in time, they are assumed to be representative of the microphysics throughout the measurement period. Among the aircraft instruments were 15 μm and 100 μm resolution cloud imaging probes (CIPs): CIP-15 and CIP-100 respectively. These were fitted with anti-shatter Korolev-tips to minimise contamination of the sample area by particle shattering [*Korolev et al.*, 2011]. At 1338 UTC, the aircraft made an overpass at 3650 m (-10.5°C) in order to sample the crystals that were producing the bi-modal feature. Later, at 1358 UTC, the aircraft another overpass at 4900 m (-17°C) to sample the crystals that were falling into the region of interest from above.

Figure 15 shows example images from the CIP-100 (left) and CIP-15 cloud imaging probes (right) at 1357 UTC during the 4900 m (-17°C) flight run. The CIP-100 image clearly shows that the ice crystals present at this temperature are small irregular polycrystals and

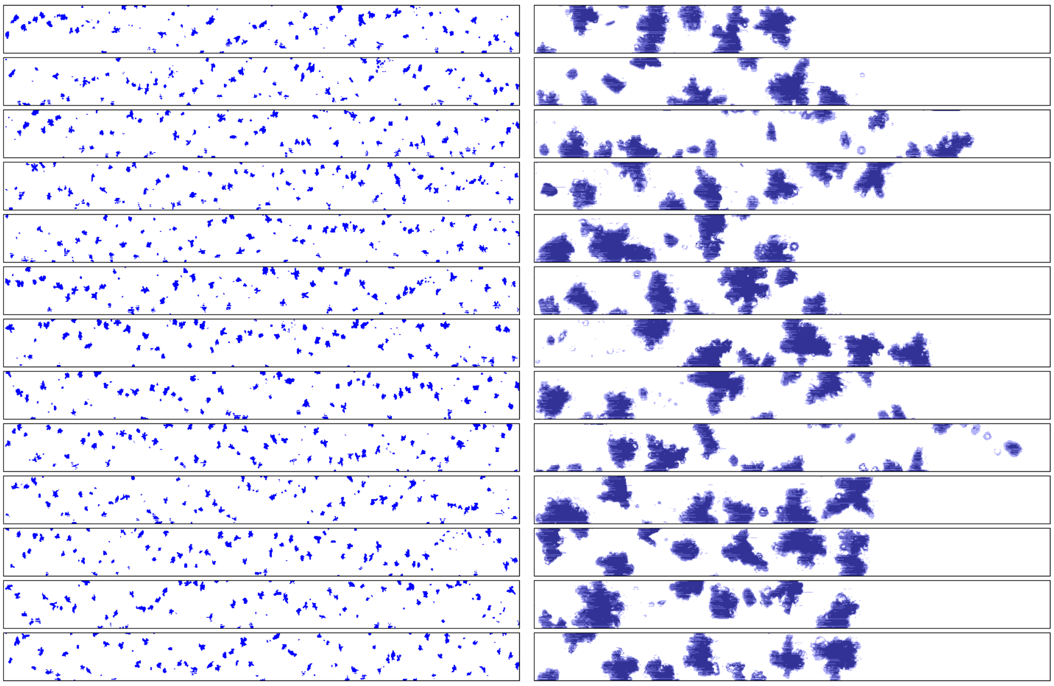

Figure 15. Example CIP-100 (left) and CIP-15 (right) images from the 4900 m (-17.5°C) flight run at 1357 UTC. The image widths are 6400 and 960 microns respectively.

aggregates, with typical major dimensions of 1 mm, with occasional crystals as large as 2 mm. This is confirmed from the CIP-15 image; the higher resolution of this image reveals the highly irregular nature of these crystals. These crystals likely nucleated at temperatures below -20°C [*Bailey and Hallett*, 2009], and have fallen to the warmer temperatures in which they are now observed.

Figure 16 shows CIP-100 and CIP-15 images from the 3650 m (-10.5°C) flight level. The CIP-100 image shows that the particles are predominantly irregular and typically larger at this temperature; large polycrystals and some aggregate crystals can be identified. This is consistent with the increase in backscattered power and gradual increase in fall speeds observed in the Doppler spectra. The CIP-15 images reveal that amongst these crystals, plate-like pristine crystals with extensions [*Magono et al.*, 1966] are present. These crystals are likely those nucleated at the height of the bi-modal feature (≈ 4.3 km, and have fallen to the height in which they were sampled by the aircraft. The apparent random orientation of these crystals is due to local accelerations as they were drawn into the probe [*Gayet et al.*, 1993]. Laboratory experiments show that the branchlike structures observed tend to form when plates crystals grow preferentially at the corners in highly saturated environments, typically

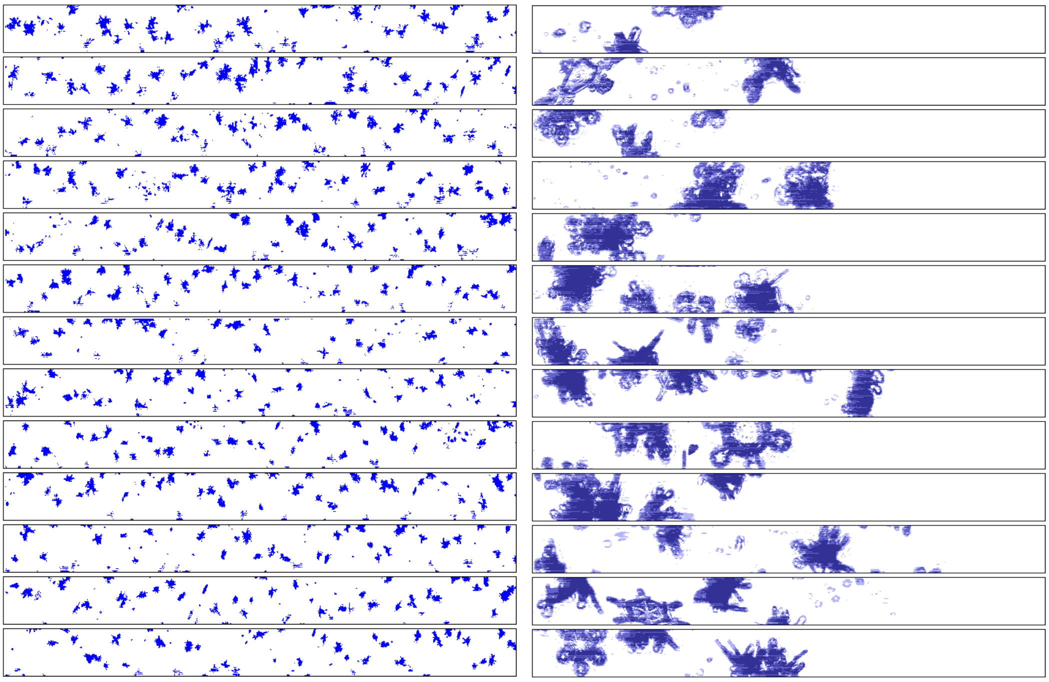

Figure 16. Example CIP-100 (left) and CIP-15 (right) images from the 3650 m (-10°C) flight run at 1338 UTC. The image widths are 6400 and 960 microns respectively.

between -13.5 and -14.5°C [*Takahashi et al.*, 1991; *Takahashi*, 2014]. This is precisely the temperature in which these crystals have grown. These in-situ measurements are further evidence that the conceptual model used in the retrieval is realistic, and that the polarimetric retrieval results are physical. It also corroborates the interpretation that reductions in retrieved Z^P_{DRI} whilst C is elevated is the result of plates growing extensions or branches, which reduces their effective density.

8 Discussion

The bi-modal cloud radar Doppler spectra and the in-situ aircraft measurements support our interpretation of the polarimetric measurements as regions of formation and growth of new pristine ice crystals, and provide encouraging evidence of a physical retrieval. However, the retrieval is sensitive to the choice of aggregate Z^A_{DRI} which we do not know precisely. This is unfortunate, as, in particular for Case II, the polarimetric signatures are relatively weak, and all but the strongest $L - Z_{DR}$ measurements are located in the part of the forward model most sensitive to this assumption (figure 8). In the retrievals, a value of 0.15 dB is chosen, which is the middle of the range of Z_{DR} thought to be typical for aggregates [*Ryzhkov and Zrnic*, 1998a; *Ryzhkov et al.*, 2005]. Ideally, this value should be constrained or measured, for example by using the observed Z_{DR} above the region of embedded pristine oriented crystal growth. This is difficult in practice as the state of aggregation of pristine crystals is not known a priori, so there is no obvious height at which to sample this “background" Z_{DR}. There is observational evidence that the background Z_{DR} above the embedded mixed-phase regions of interest is in fact larger than the Z_{DRI}^{A} used here. This is supported by observations of $Z_{DR} > 0.3$ dB in regions that exlusively contain a monodisperse population of irregular polycrystals and aggregates (as seen in the CIP-15 and CIP-100 images measured at 4900 m in case study II). It is interesting to note that an underestimated Z_{DRI}^{A} would lead to systematically smaller C retrievals from the polarimetric technique, which would bring them into closer agreement with comparable C estimates from the Doppler spectra. However, their imperfect co-location means they may not be expected to necessarily agree. Furthermore, an underestimated Z_{DRI}^{A} would also lead to an underestimate in retrieved Z_{DRI}^{P}. It would be interesting to investigate whether this value can be better constrained. For example, it could be that the Z_{DR} of aggregates and polycrystals would be better characterised as a function of temperature.

The retrieval assumes that pristine oriented crystals have a fixed aspect ratio (and by defining ρ_{hv}^{P} in equation 23, it is demonstrated that the retrieval is relatively insensitive to this). Therfore, $\rho_{hv}^{P} = 1$ is assumed in the presented retrievals. However, this assumption would not hold if the technique is used to retrieve Z_{DRI}^{P} in regions that are known to be columns (such as in Hallet-Mossop ice multiplication zones). Unlike plates, the maximum Z_{DR} that can be produced by a distribution of columns is 4 dB, since they fall with random azimuthal orientation and the total backscatter in the H polarisation must be integrated over all azimuthal angles (see figure 1). This random azimuthal orientation also has the effect of increasing the shape diversity of the ice crystals from the perspective of the radar; the observed ρ_{hv} for a mixture of columns-only with fixed aspect ratios would be lower than for plates-only. Therefore, this effect could be conveniently characterised in the retrieval by modifying the ρ_{hv}^{P} value in equation 23. The ρ_{hv}^{P} would be highest for isometric columns, which would look nearly the same to the radar regardless of azimuthal orientation, and lowest for longer, thinner columns or needles, which would increase the shape variety from the perspective of the radar. In effect, ρ_{hv}^{P} would be a function of Z_{DRI}^{P} for a distribution of columns (with fixed aspect ratios). This is something that would be interesting to develop further in future work.

Unfortunately, the enhanced Z_{DR} and decreased L signature observed between 1.5 and 2.5 km in height in Case II was too weak for a reliable retrieval. However, evidence that this signature is associated with new pristine crystal growth comes from clear bimodality in the Doppler spectrograph (figure 13) at this height. The signature occurs within the range of temperatures in which the Hallet-Mossop process is known to operate [*Hallett and Mossop*, 1974]. This hypothesis is supported by the presence of a large number of needles that are observed by the CIP probes at 1800 m (not shown). In addition, the aircraft Cloud Droplet Probe (CDP) detected the presence of both small (<13 μm) and large (>24 μm) liquid water drops here that are thought to be required for the Hallet-Mossop process to operate [*Hallett and Mossop*, 1974]. In future, the polarimetric retrieval technique presented could be used to locate and study regions of secondary ice production.

It is important to note that the vertical profiles used in the retrieval are obtained from RHI scans, therefore contain observations from a range of elevation angles. As the radar elevation angle increases, the V polarised wave increasingly samples the same plane as the H polarised wave. This means that Z_{DR} measurements of all particles at higher elevations will be reduced from the perspective of the radar. Before the retrieved Z_{DRI}^{P} signatures can be interpreted microphysically, they should be corrected to the “true" Z_{DRI}^{P}, $Z_{DRI}^{P}(0)$, i.e. that at horizontal incidence. The peak elevation angles included in the retrieval for Cases I and II are 23 and 28° respectively. The temperatures at which the polarimetric signatures are observed (and evidence from aircraft imagery during the second case study) show that the pristine crystals in these cases are plate-like, therefore $Z_{DRI}^{P}(0)$ can be readily calculated using the modified Gans equations of *Westbrook* [2014]. For the elevation angles in these case studies, the average $Z_{DRI}^{P}(0)$ in the retrieval profiles is approximately 2 dB larger than Z_{DRI}^{P}. Full details of this correction can be found in the appendix of *Keat* [2016].

9 Conclusions

A novel polarimetric retrieval technique is developed that uses ρ_{hv} and Z_{DR} to separate the radar reflectivity contributions from pristine oriented crystals from the larger crystals they are forming amongst, overcoming the well-known “masking" effect of aggregates. The technique allows the intrinsic Z_{DR} of pristine crystals and their relative contribution to radar reflectivity to be retrieved. Two case studies are presented, both of which contain retrieval profiles with broadly similar characteristics. They reveal that enhancements of Z_{DR} embedded within deep ice are typically produced by pristine oriented crystals with large Z_{DRI}^{P} values between 3 and 7 dB (equivalent to 5—9 dB at horizontal incidence), but with varying contributions to the radar reflectivity. Pristine oriented crystals were nucleated at -14 to -15°C embedded amongst irregular polycrystals and aggregates in deep ice clouds. They grew rapidly by vapour deposition, and later aggregated, indicated by their decreasing relative contribution to the radar reflectivity. The technique can be applied even in relatively poor SNR conditions, at the expense of additional uncertainty in the retrieved profiles.

Coincident Doppler spectra from the zenith pointing 35 GHz Copernicus cloud radar and in-situ aircraft measurements during the second case study support the conceptual model used to develop the polarimetric retrieval technique, and provide evidence of a physical retrieval. At the height of an enhanced polarimetric signature, bi-modal Doppler spectra were observed which indicated the presence of two crystal populations; one falling more slowly (more recently formed pristine oriented crystals with extreme aspect ratios) and one falling more quickly (aggregates). By integrating the power spectrum over the expected velocity ranges for each crystal population, an equivalent C is estimated that is qualitatively similar to that retrieved using the polarimetric method. In-situ measurements from cloud imaging probes on-board the FAAM BAe-146 aircraft show that at the location of the enhanced L—Z_{DR} feature, plate-like crystals with extensions were growing amongst polycrystals and aggregates, supporting the conceptual model used in the retrieval.

Retrieved C and Z_{DRI}^{P} are shown to be sensitive to the assumption of the Z_{DR} of aggregate crystals the pristine oriented crystals are growing amongst. A better constraint on this value would be useful to improve the retrieval.

More case studies are required to fully assess the retrieval. However, we foresee this technique facilitating further improvements in our understanding of the microphysics of embedded mixed-phase clouds. One interesting avenue of future work would be to combine C and Z_{DRI}^{P} with measurements of K_{DP}, which is only sensitive to the number and shape of aligned particles. For example, Z_{DRI}^{P} and K_{DP} could be used to estimate ice water contents of the pristine crystals using a method similar to *Ryzhkov and Zrnic* [1998b]. There is also the potential for application in an operational environment, where it could aid the identification of hazardous aircraft icing regions.

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