Correction for attenuation of radar reflectivity using polarization data

By T. J. SMYTH* and A. J. ILLINGWORTH

University of Reading, UK

(Received 4 September 1997; revised 11 May 1998)

SUMMARY

Attenuation by heavy rain is a major operational problem in radar estimation of rainfall rates, and one which is increasingly severe at wavelengths shorter than 10 cm. Gate-by-gate correction algorithms, including those using both reflectivity (Z_H) and differential reflectivity (Z_{DR}), are inherently unstable. In addition values of Z_H and Z_{DR} are affected by hail, which causes little attenuation. Methods dependent upon differential phase shift (K_{DP}) do not give unique solutions but depend upon raindrop size distributions. A new technique which uses both K_{DP} and differential attenuation between the horizontally and vertically polarized radiation (A_{H-V}) is proposed. The total A_{H-V} is measured from the negative Z_{DR} in light precipitation behind the attenuating region. Theory and observation show that corrections based on the K_{DP} = A_{H-V} scheme should be unaffected by hail, stable and accurate. A simpler algorithm may be feasible at C-band in which the total attenuation is derived from the observed total differential attenuation. It appears that the most severe cases of attenuation result from heavy rain consisting of large oblate raindrops. Accordingly, the attenuation would be appreciably reduced if operational radars used vertical polarization rather than the commonly employed horizontal polarization.

KEYWORDS: Heavy rain Rainfall estimation Vertical polarization

1. INTRODUCTION

If reliable rainfall rates for regions of intense precipitation are to be calculated using radar, then correction for attenuation is necessary. Attenuation becomes increasingly more serious as the wavelength, \( \lambda \), is reduced. At S-band (\( \lambda = 10 \) cm) the effect has previously been considered to be negligible (Hitschfeld and Bordan 1954), whereas C-band (\( \lambda = 5 \) cm; the wavelength of many operational radars in Europe) attenuation due to precipitation is well known to disrupt rainfall rate estimation. The gate-by-gate attenuation correction scheme of Hitschfeld and Bordan (1954) which relies on a relationship between attenuation, \( A \), and reflectivity, \( Z \), is known to be very unstable and, as shown by Hildbrand (1978), extremely sensitive to calibration errors. Delrieu et al. (1991) have computed relationships between \( A \) and \( Z \) for different wavelengths, temperatures and drop size distributions (DSDs) assuming the raindrops to be spherical. They show that at C-band the attenuation at 20 °C is typically about 75% of the value at 0 °C and, for example, that for a 100 mm hr^-1 rainfall rate and 0 °C they predict that different DSDs can give one-way attenuations ranging from 0.43 to 0.67 dB km^-1. For airborne radar the ‘stereoradar’ technique (Kabeche and Testud 1995) relies on observing precipitation cells from two angles. A very simple version of this technique could be used when two neighbouring radars in a network provide overlapping coverage; it is most unlikely that the paths from both radars will suffer attenuation, so only the unaffected beam is used. However, for most operational networks such overlapping regions are not widespread. Recently, Delrieu et al. (1997) reported a ground-based version of the ‘surface reference technique’ developed for spaceborne radars. This method, using an X-band radar in mountainous terrain, relies on measuring the reflectivity of a well-defined distant clutter target when there is attenuation to estimate the path integrated attenuation, and then using this as a constraint for the gate-by-gate retrieval. Such a technique may be appropriate at X-band where attenuation is very severe, but the accuracy is limited, for example, by the day-to-day variation of about 3 dBZ in the apparent reflectivity of the clutter target in dry weather.

* Corresponding author, present address: Plymouth Marine Laboratory, Prospect Place, Plymouth, Devon PL1 3DH, UK. c-mail: T.J.Smyth@pml.ac.uk.
This paper presents observations of a severe convective event on 7 June 1996, which caused severe differential attenuation \((A_{H-V})\) between the horizontally polarized \((A_H)\) and vertically polarized \((A_V)\) copolar returns of up to 5 dB, by the S-band Chilbolton multi-parameter radar in southern England. Rapid-response raingauges, situated 500 m below the precipitation region causing the radar attenuation, measured values in excess of 250 mm \(\text{hr}^{-1}\). A numerically stable algorithm to correct for reflectivities measured with horizontal and vertical polarizations is proposed which relies on both \(A_{H-V}\) and differential phase shift \((\phi_{DP})\).

2. Definition of radar parameters

Differential reflectivity is defined as (Seliga and Bringi 1976):

\[
Z_{DR} = 10 \log_{10} \frac{Z_H}{Z_V} \quad \text{(dB)},
\]

where \(Z_H\) and \(Z_V\) are the backscattered reflectivity in the horizontal and vertical polarizations respectively. \(Z_{DR}\) is a measure of the reflectivity-weighted oblateness (Jameson 1983). Raindrops are oblate to a degree which increases with size, and fall with their minor axis oriented vertically. Rain can therefore be described as an anisotropic medium. High positive values of \(Z_{DR}\) are associated with large oblate raindrops.

The one way absolute attenuation, using the formulation of Oguchi (1973), is defined as:

\[
A_H = 8.686 \times 10^3 \lambda \int \text{Im}[S_{H}(D_e)] N(D_e) \, dD_e \quad \text{(dB km}^{-1} \text{)},
\]

where \(D_e\) is the spheroid equivolumetric diameter of the drops, \(\text{Im}(S_{H}(D_e))\) (m) is the imaginary component of the forward-scatter amplitude in the horizontal polarization and \(N\) is the number of particles per unit size per unit volume. When dual polarization radar illuminates a region filled with oblate spheroids oriented with their minor axes vertical, such as in rain, the horizontal polarization will become attenuated to a greater extent than the vertical. This differential attenuation is defined as:

\[
A_{H-V} = 8.686 \times 10^3 \lambda \int \text{Im}[S_{H}(D_e) - S_{V}(D_e)] N(D_e) \, dD_e \quad \text{(dB km}^{-1} \text{)},
\]

where \(S_V\) is the forward-scattering amplitude (m) for vertically polarized waves. A factor of two is required in (2) and (3) to account for two-way attenuation. \(A_{H-V}\) can be deduced by the magnitude of negative \(Z_{DR}\) in light precipitation behind an attenuating region. In these regions \(Z_{DR}\) should be close to zero as the raindrops will be approximately spherical. For example, if \(Z_{DR}\) is \(-2\text{ dB}\) in light rain then the total path integrated \(A_{H-V}\) along the ray is 2 dB.

The differential phase shift, \(\phi_{DP}\), is the difference in phase between the copolar radar returns measured with vertical and horizontal polarization \((\phi_V - \phi_H)\). \(\phi_{DP}\) is made up of three contributions: a propagation component \((K_{DP})\), which is a function of range, differential phase shift on backscatter (\(\delta\)) and a hardware offset \((\phi_o)\), i.e.

\[
\phi_{DP}(r) = 2 \int_0^r K_{DP}(r) \, dr + \delta(r) + \phi_o \quad \text{(')},
\]

where \(r\) is the range. \(K_{DP}\) is defined as:

\[
K_{DP} = 2 \times \frac{180 \times 10^3 \lambda}{\pi} \int \text{Re}[S_{H}(D_e) - S_{V}(D_e)] N(D_e) \, dD_e \quad \text{(' km}^{-1} \text{)}.
\]

\[\]
The factor of two is for two-way propagational differential phase shift, and the factor of $10^3$ is a conversion from $\circ \text{ m}^{-1}$ to $\circ \text{ km}^{-1}$. As the incident wave propagates through a region of rain the horizontally polarized wave lags progressively behind the vertical one, because raindrops display a high degree of anisotropy. This causes a positive differential phase shift. In rain the value of $K_{DP}$ is approximately proportional to the rain-rate, $R$. A relationship of the form:

$$K_{DP} = 0.03 R^{1.15} \quad (\circ \text{ km}^{-1})$$

(6)

at S-band has been proposed by Sachidananda and Zrnić (1986). At S-band $\delta$ is usually considered to be very small, as it only occurs in the Mie regime, that is for raindrops of size 7 mm and rather larger for dry hailstones; it is only measurable if the hydrometeors have a preferred orientation (McCormick et al. 1979), not if randomly oriented. It is important to note that $\delta$, being a backscatter effect, is a transitory change in $\phi_{DP}$ superposed on the general propagation effect, and can introduce ambiguity in the interpretation of the signal. The observed $\delta$ for a distribution of scatterers in the pulse volume can be calculated using the cross correlation coefficient $\rho_{HV}$:

$$\rho_{HV} = \frac{\int S_{bh}(D_e) S_{hv}^*(D_e) N(D_e) \, dD_e}{[\int |S_{bh}|^2 N(D_e) \, dD_e]^{1/2} [\int |S_{hv}|^2 N(D_e) \, dD_e]^{1/2}}$$

(7)

$$\rho_{HV} = |\rho_{HV}| \exp(j\delta),$$

(8)

where $S_{bh}$ and $S_{hv}$ are the backscatter amplitudes in the horizontal and vertical, and the units of $\delta$ are radians.

3. **Attenuation correction algorithms**

(a) **Single parameter**

Several attenuation correction algorithms have been derived and implemented on both actual and simulated data. The simplest algorithms involve the use of reflectivity-only ($Z$-only) data (see e.g. Hitschfeld and Bordan (1954) and Hildebrand (1978)), are generally gate-by-gate iterative schemes and prove to be highly numerically unstable. The UK Meteorological Office (UKMO) attenuation correction scheme is a cumulative gate-by-gate algorithm of the form:

$$A = 0.0044 R^{1.17} \quad (\text{dB km}^{-1}),$$

(9)

for the two way attenuation (Collier 1990) based on the work of Gunn and East (1954). This procedure is prone to instability and so the predicted correction is capped; the maximum correction factor allowed is a doubling of the rainfall. This is being used operationally for all UK radars from 1998 and is similar to that in use in Sweden and Spain (A. Smith, UKMO, personal communication). A great deal of the instability in single-parameter schemes is caused by initial radar calibration (Hitschfeld and Bordan 1954). $Z$ only schemes are also unable to distinguish between rain and hail (because $Z \propto D^6$, where $D$ is the particle diameter, and contains no information about the composition of the precipitation volume) which could lead to spurious amounts of correction via the conversion to rain rate.

(b) **Dual parameter**

Aydin et al. (1989) formulated a theoretical correction algorithm for use at C-band using a combination of $Z_H$ and $Z_{DR}$. From the premise that $R$ estimates are improved by using the $Z_H$ and $Z_{DR}$ pair, it is a natural progression to the assumption that the introduction of $Z_{DR}$ should improve estimates of attenuation. Using DSDs obtained by distrometer
measurements, they modelled backscattering and extinction cross-sections to obtain the radar parameters of $Z_H$, $Z_{DR}$, and calculated $A_H$ and $A_{H-V}$. They derived empirical relationships between $A_H$ or $A_V$ and the $Z_H$, $Z_{DR}$ pair using a least squares polynomial fit. A gate-by-gate scheme was employed to produce a first-order correction, and an iteration process invoked at the $n$th gate which was repeated until the absolute difference between two consecutive approximations of $Z_H$ and $Z_{DR}$ at that gate were less than 0.1 dBZ and 0.05 dB respectively. They found, however, that those conditions were satisfied within one iteration. To test for noise and biases they simulated radar data, and found that any bias in $Z_H$ deteriorated that procedure because the errors add cumulatively. Scarchilli et al. (1993) used a similar scheme but they parametrized $A_H$ and $A_{H-V}$ in terms of $Z_H$ and $Z_{DR}$.

Tan and Goddard (1997) describe a scheme which does not rely upon a gate-by-gate iterative technique and is therefore highly numerically stable. Instead, a compensation method is used, which employs relationships between $A_H$, $A_V$ and the $Z_H$, $Z_{DR}$ pair. This is illustrated in Fig. 1, and relies on the negative slope of the $A_H/Z_H$ against $Z_{DR}$ curve. The effect of attenuation will be to reduce the observed values of both $Z_H$ and $Z_{DR}$. If the attenuated value of $Z_{DR}$ is used, rather than the true value, then the negative value of the slope in Fig. 1 means that the computed value of $A_H/Z_H$ is larger than it should be. However, if when evaluating $A_H/Z_H$ we use the observed attenuated value of $Z_H$, then the resultant predicted value of $A_H$ will be close to the true one. The errors caused by using the attenuated values of both $Z_H$ and $Z_{DR}$ thus tend to cancel out, and the calculated value of $A_H$ is closer to the true one than if $Z_H$ alone is used.
The technique, then, is to use the uncorrected values of $Z_H$ and $Z_{DR}$, and to predict a value of $A_H$ at each gate. This value of $A_H$ is then used at each gate to correct $Z_H$ on a gate-by-gate basis. When $Z_{DR}$ becomes very small the scheme is difficult to implement because of the increasingly steep slope of the curve in Fig. 1. If the attenuation is so large that $Z_{DR}$ becomes negative then an alternative approach is needed. Tan and Goddard (1997) suggest using a relationship between $A_H$ and $A_{H-V}$:

$$A_{H-V} = A_H - A_V \quad (\text{dB km}^{-1}),$$

$$A_H \simeq 2.95 \times A_{H-V} + 0.084 \quad (\text{dB km}^{-1}),$$

this relationship being empirical and unique to C-band. An iterative step is invoked if any negative values of $Z_{DR}$ remain.

The fundamental difficulty with all $Z_H - Z_{DR}$ schemes is the assumption that only rain is present. When hail occurs $Z_H$ increases and $Z_{DR}$ falls, and such schemes will erroneously infer exceptionally heavy rain consisting of small drops, with consequently spurious high levels of attenuation.

(c) Differential phase scheme

$\phi_{DP}$ is ideally suited for use in an attenuation correction algorithm, because it has similar features to $A_H$ and $A_{H-V}$. Both are forward-scatter effects; the real part of the forward-scatter amplitudes is proportional to $K_{DP}$ whereas the imaginary part is proportional to attenuation. $\phi_{DP}$ itself is not affected by attenuation as it measures the difference in phase, and it is also relatively unaffected by hail. An additional factor is that raindrops become more oblate with increasing size, implying that $K_{DP}$ increases with increased specific differential attenuation which implies that there is some form of relationship between the two parameters.

The use of $\phi_{DP}$ to correct for attenuation was first suggested by Bringi et al. (1990) and their calculations have been re-worked in section 5. They suggested the use of linear relationships between $K_{DP}$ and both $A_H$ and $A_{H-V}$. As will be shown in section 5, the use of a single linear relationship is equivalent to assuming a constant value of the median DSD diameter, $D_0$ (mm), but allowing the concentration of drops, $N_0$ (m$^{-3}$mm$^{-1}$), to vary in the standard exponential rain DSD e.g.

$$N(D) = N_0 \exp \left( \frac{-3.67 \times D}{D_0} \right) \quad \text{m}^{-3}\text{mm}^{-1},$$

where $N_0$ is the intercept of the curve on the $N$ axis. In their simulations Bringi et al. (1990) did not allow $D_0$ to rise above 2.5 mm, a very low value for heavy precipitation.

4. Observations

In this paper we propose a method of correcting for attenuation which involves both differential phase shift and the accumulated differential attenuation (i.e. negative $Z_{DR}$ on the far side of the storm). An example is shown in Fig. 2 where the differential attenuation and differential phase shift are clearly visible behind shafts of heavy rain. The ‘stripes’ of negative $Z_{DR}$ and phase shift emanate from a region behind an intense rainfall shaft (where $Z_{DR}$ is $> 4$ dB) in a manner analogous to a shadow, pointing to the region where attenuation is occurring. Two regions of $A_{H-V}$ are apparent from Fig. 2 along radials of 270° and 240°. Also shown in Fig. 2 are the positions of two rapid-response drop counting gauges (g5 and g7) which provided 30-second resolved rain rate estimates.
Ryzhkov and Zrnić (1994) draw attention to the existence of differential attenuation accompanying large values of differential phase shift. Although the ray profile they show is very noisy, with $50^\circ$ noise on $\phi_{DP}$ and 1 dB on $Z_{DR}$, they present a statistical analysis suggesting the amount of $A_{H-V}$ for a given $\phi_{DP}$ is about twice as much as predicted by Bringi et al. (1990).

5. SCATTERING CALCULATIONS

(a) Hail

The scattering coefficients for hailstones of various structural compositions, i.e. dry, spongy (30% water-ice mixture) or covered with a layer of water, were extracted using the T-matrix code (Waterman 1965), and the effect of shape and alignment investigated. The dielectric constants for water and ice were those calculated by Ray (1972) and Liebe et al. (1989). Dry hail (hail above the melting layer) was modelled using the dielectric constant of dry ice ($3.15 + 0.0004i$; at $0^\circ C$ and $\lambda = 9.75$ cm). In all cases there is no air contained in the mixture. Spongy hail contains water within a frozen ice lattice and can be considered to be a homogeneous mixture of the two; the dielectric constant can be extracted using the Bruggemann rule (O’Brien and Geodecke 1988). Wet hail was modelled using both
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Figure 3. S-band comparison of horizontally polarized backscatter reflectivity, $Z_H$ against attenuation, $A_H$, for hail varieties and Marshall-Palmer drop size distribution (MP) rain at $0^\circ$C. $\gamma$ from (13) is varied between 0.1 and 2 mm$^{-1}$ for all hailstone compositions. See text for further explanation.

The concentration of the hailstones was modelled using the exponential DSD empirically derived by Cheng and English (1983):

$$N(D_e) = 115\gamma^{3.63} e^{-\gamma D_e} \text{ (m}^{-3} \text{ mm}^{-1}),$$

where $D_e$ is in mm. Using the hail data, Cheng and English found that $\gamma$ did not fall outside the range of 0.1–2.0 mm$^{-1}$.

Figure 3 shows a comparison between the amounts of $A_H$ resulting from spherical hailstones, and Marshall and Palmer (1948; MP; $N_0 = 8000 \text{ m}^{-3} \text{ mm}^{-1}$ in (12)) rainfall. The hail data points in Fig. 3 refer to the different physical compositions. Within each physical category $\gamma$ in (13) is varied between 0.1 and 2.0 mm$^{-1}$. These calculations, which are displayed in Fig. 3, suggest that at S-band most attenuation is produced when $Z_H > 60 \text{ dBZ}$, and that the hail contributes very little to the attenuation because it is present in such low concentrations. Because of these low concentrations, the $K_{DP}$ of hail is much less than that of rain even if it is wet, aligned and oblate.

(b) Rain

To model the effect of rain, a normalised gamma DSD (14) was used (Blackman 1996) in preference to the gamma DSD and its associated relationships proposed by Ulbrich.
Figure 4. S-band propagation, $K_{DP}$, as a function of attenuation, $A_R$, using Beard and Chuang (1987) shapes at 20°C, with various values of raindrop concentration, $N_0$, in the drop size distribution ($\mu = 0$). The $N_0 = 8 \text{ m}^{-3} \text{ mm}^{-1}$ line is shorter as all the data points for equivolumetric diameters, $D_0$, varying between 0 and 10 mm are contained within the axis bounds.

(1983):

$$N(D_e) \, dD_e = \frac{N_0}{|\mu|!} (\Gamma D_e)^\mu e^{-\Gamma D_e} \, dD_e \quad (\text{m}^{-3}),$$

(14)

and

$$\Gamma = \frac{(3.67 + \mu)}{D_0} \quad (\text{mm}^{-1}),$$

(15)

where $\mu$ describes the form of the distribution. Studies using radar have found $\mu$ to vary between 0 and 5 (Wilson et al. 1997), and 2 and 4 (Illingworth and Caylor 1989). A distrometer study by Goddard and Cherry (1984) showed $\mu$ to be closer to 5. In this paper, to obtain the variability found in naturally occurring rain, we vary $\mu$ between 0 and 5 in the normalised gamma DSD of (14). The shapes of Beard and Chuang (1987) were used in preference to those of Green (1975) and Pruppacher and Pitter (1971); Caylor (1989) found that Beard and Chuang shapes gave the best approximation to what was observed by the Chilbolton radar in naturally occurring rain.

Figures 4 and 5 are a re-working of Bringi et al. (1990) calculations of the relationships between $A_H$ and $A_{H-V}$ against $K_{DP}$ for various raindrop size spectra. Bringi et al. considered that a $D_0$ of 2.5 mm was the maximum likely to occur. A $D_0$ of 2.5 mm is equivalent to a $Z_{DR}$ of 3 dB, yet values of $Z_{DR}$ up to 6 dB are observed in rain; so in Figs. 4 and 5 we have extended values of $D_0$ up to 7 mm and truncated the spectrum at 10 mm. (The curves plotted are for pure exponentials with $\mu = 0$.) Whereas Bringi et al. found a single relationship linking $K_{DP}$ to the two attenuation coefficients, the inclusion of larger mean drop sizes leads to a family of curves predicting higher attenuation for a given $K_{DP}$.

$K_{DP}$, $A_H$ and $A_{H-V}$ are all proportional to $N_0$ (see (2), (3), and (5)), so in Figs. 4 and 5 lines of constant $D_0$ are straight lines through the origin, with $N_0$ varying along the straight
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Figure 5. As Fig. 4, but $K_{DP}$ as a function of differential attenuation, $A_{H-V}$.

The proposed single linear relationship of Bringi et al. between $K_{DP}$ and both $A_H$ and $A_{H-V}$, is then equivalent to assuming that in attenuating rainfall $D_0$ is constant and equal to 2.5 dB, and $Z_{DR}$ (when corrected for attenuation) is constant in the rain at 3 dB.

Also shown in Fig. 4 and 5 are the lines of constant $N_0$ showing, for example, that the $D_0 = 7$ mm line initially intercepts the $N_0 = 8 \text{ m}^{-3} \text{ mm}^{-1}$ and then, when $K_{DP} = 18 \text{ km}^{-1}$, $N_0 = 80 \text{ m}^{-3} \text{ mm}^{-1}$. The graph for $N_0 = 8 \text{ m}^{-3} \text{ mm}^{-1}$ corresponds to a low concentration of increasingly large raindrops, and the line is terminated when the value of $D_0$ is so big that the rainfall rate becomes unrealistically large. Because the spectra are truncated at 10 mm these high $D_0$ spectra are effectively almost monodispersed, containing only very large raindrops. It needs to be noted that the relationships shown in Figs. 4 and 5 are sensitive to changes in $\mu$. However, for the purposes of attenuation correction outlined in section 6, these effects are small.

The only difference between the calculations of $K_{DP}$ and $A_H$ for a given $N_0$, $D_0$ and $\mu$, ignoring the constant terms, is that $K_{DP}$ is proportional to the real part of the forward scatter amplitude whereas $A_H$ is proportional to the imaginary part. Therefore any differences between the two parameters should become apparent when the scattering coefficients are studied closely. Figure 6 provides an explanation of the behaviour shown in Fig. 4. Once the raindrop size is larger than 3 mm the real part of the forward scatter amplitude increases less rapidly than the imaginary part. This means that there is more attenuation for a given phase shift for the larger drops, confirming the trend in Figs. 4 and 5. In physical terms, Fig. 4 suggests that the greatest amount of attenuation is caused by a small number of large drops being present within the radar volume. The implication follows that there are not simple linear relationships between attenuation and $K_{DP}$. Any method purporting to correct for total attenuation must have information on both the $N_0$ and $D_0$ of the rainfall spectrum causing the attenuation.
Figure 6. S-band variation of the forward scattering amplitude, $S_m(m)$ as a function of diameter, at 20 °C using Beard and Chuang (1987) shapes. See text for further explanation.

Attenuation is strongly dependent upon temperature (Jameson 1992), this is because the attenuation rate is controlled by molecular absorption and scatter out of the beam. Molecular absorption (the imaginary component) is enhanced at lower temperatures, and is dominant at the frequencies of 3 and 5 GHz over almost all raindrop sizes. This is shown in Fig. 7. At 20 °C the value of $\text{Im}(S_m)$ is 40% less than when the temperature is 0 °C over a large range of the raindrop sizes. This implies that when using model results to correct for attenuation, great care must be taken in selecting a representative temperature for the raindrops.

6. CORRECTION SCHEME

The attenuation correction algorithm proposed in this paper which uses the two propagation observables, $K_{DP}$ and the total amount of $A_{H-V}$, is outlined in Fig. 8. The total amount of $A_{H-V}$ is estimated from the negative $Z_{DR}$ beyond the intense precipitation, and is partitioned amongst the gates where $K_{DP} > 10 \text{ km}^{-1}$ with a weighting proportional to the magnitude of $K_{DP}$. Values of $N_0$ and $D_0$ are derived from $A_{H-V}$ and $K_{DP}$ (as in Fig. 5) at each gate, and $A_H$ is computed at that gate. The corrected values of $Z_H$ and $Z_{DR}$ are then found from $A_H$ and $A_{H-V}$ at each gate. The highest values of attenuation occur in the regions of low $N_0$ and high $D_0$, and are only slightly affected by changes in the assumed value of $\mu$.

The values of $N_0$ and $D_0$ are uniquely defined in $K_{DP}/A_{H-V}$ space, if the value of $\mu$ in the DSD is predetermined, and the value of $A_H$ can be computed at each gate. There are small errors in estimating $A_H$ in this manner because the lines of constant $N_0$ and $D_0$
Figure 7. The variation of the forward scatter coefficient, $\text{Im}(S_m)$, with temperature, $T$, and equivolumetric diameter at S-band using Beard and Chuang (1987) shapes and the dielectric constant of water. See text for further explanation.

Find minimum value of $Z_{\text{dr}}$

Total amount of differential attenuation

Find total phase change through regions of sig attenuation

Value of $K_{dp}$ at each gate within sig attenuation region

Find weighting for each gate $K_{dp}$

$\text{phidp(total)}$

Weight this to find $A(h-v)$ at each gate

Find weighting for each gate $K_{dp}$

$\text{phidp(total)}$

$A(h)$

$A(h-v)$

Derive $N_0$ & $D_0$

Calculate $A(h)$

at each gate

Cumulative corrected

$Z_h$

$Z_{\text{dr}}$

at each gate

Figure 8. Flow diagram of the attenuation correction scheme. Criterion: Significant attenuation occurs in gate where uncorrected $Z_h > 30$ dBZ and $K_{dp} > 10$ km$^{-1}$. See text for further details.
TABLE 1. S-BAND VARIATION OF \(A_H\), \(N_0\) AND \(D_0\) FOR A FIXED VALUE OF \(A_{H-V}\) (0.25 dB km\(^{-1}\)) AND VARIABLE \(K_{DP}\) AT 20 °C FOR \(\mu = 0\).

<table>
<thead>
<tr>
<th>(K_{DP}) (cm(^{-1}))</th>
<th>(A_H) (dB km(^{-1}))</th>
<th>(N_0) (m(^{-3}) mm(^{-1}))</th>
<th>(D_0) (mm)</th>
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<tr>
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<td>600</td>
<td>4.00</td>
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<tr>
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</table>

For consistency see Figs. 4 and 5.

TABLE 2. AS TABLE 1 BUT FOR \(\mu = 2\).

<table>
<thead>
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<th>(A_H) (dB km(^{-1}))</th>
<th>(N_0) (m(^{-3}) mm(^{-1}))</th>
<th>(D_0) (mm)</th>
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<tbody>
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</table>

are almost parallel in \(K_{DP}/A_{H-V}\) space, as shown in Fig. 5 for \(D_0 < 7\) mm. This means that for a fixed value of \(A_{H-V}\) and allowing \(K_{DP}\) to vary (to simulate random errors in the measurement of \(\phi_{DP}\)), changes in \(D_0\) are compensated for by changes in \(N_0\). Table 1 highlights this point for a fixed \(A_{H-V}\) of 0.25 dB km\(^{-1}\). For example, if the value of \(K_{DP}\) is 15 ± 2 cm\(^{-1}\) (realistic measurement error), then the associated value of \(A_H\) for a fixed \(A_{H-V} = 0.25\) dB km\(^{-1}\) is 0.37 ± 0.04 dB km\(^{-1}\). In other words, a 14% error in the measurement of \(K_{DP}\) will lead to a 11% error in the estimated value of \(A_H\). If the total attenuation suffered by the beam is of the order of 5 dB, to have corrected \(Z_H\) to within 0.5 dB is more than satisfactory as it corresponds to an accuracy of derived rainfall rate of better than 10%.

Once the individual gate’s value of \(A_H\) and \(A_{H-V}\) are known, the corrected values of \(Z_H\) and \(Z_{DR}\) can be extracted by cumulatively summing the attenuation parameters. This scheme is not numerically unstable, as any error at a particular gate does not contribute to successive gates, unlike iterative gate-by-gate methods. It is also physically based, the measured parameters being used to compute components of the DSD rather than relying upon a mathematical compensation effect as in the scheme of Tan and Goddard (1997). The scheme is also insensitive to hail which should not contribute to \(A_{H-V}\) or \(K_{DP}\). However, within the scheme there are flaws. For each particular attenuation event \(A_{H-V}\) is divided between the gates depending upon the \(K_{DP}\) weighting, thus the attenuation corrected points are constrained upon a line of constant \(D_0\), the coincidental values of \(N_0\) being allowed to vary. This is easier to envisage with the aid of Fig. 5. \(D_0\) is, in effect, defined over the whole precipitation core responsible for the attenuation, rather than allowing for any gate-to-gate variation which is possible within heavy storms over short spatial scales.

Comparing Tables 1 and 2 shows that the scheme is insensitive to \(\mu\) variation for the purposes of calculating \(A_H\) from the \(K_{DP}, A_{H-V}\) pair. There appears to be a compensation effect between \(D_0\) and \(N_0\), with the result that there is only a 2.5% difference between the \(A_H\) calculated using \(\mu = 0\) and that using \(\mu = 2\). A fixed value of \(\mu\) can therefore be used within the scheme.
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Figure 9. Attenuation, $A_H$, as a function of propagation, $K_{DP}$, for $\mu = 0$ at 20 °C. The data points are taken from several scans on 7 June 1996 as part of the correction scheme. See text for further details.

Figure 9 shows that most of the data points lie along the line of $N_0 = 800 \text{ m}^{-3} \text{ mm}^{-1}$ with a $D_0$ of between 2.5 and 5 mm. The maximum value of $D_0$ used in the calculations of Bringi et al. was 2.5 mm. These results show that larger values of $D_0$ need to be considered and that the drop size spectrum should include raindrops of diameters up to 8 or 10 mm. There is a considerable departure from the $A_H = 0.016K_{DP}$ line in Fig. 9, which suggests that a different linear relationship exists for each value of $D_0$; this is consistent with the theoretical scattering calculations presented in Figs. 4 and 5. In short, the precise composition of the DSD has a large bearing upon the relationship between $K_{DP}$ and the attenuation parameters, especially when it comprises a low concentration of large drops, and this is the advantage of implementing the attenuation algorithm detailed above. The scheme essentially defines an $N_0$, $D_0$ pair for a fixed value of $\mu$ in $K_{DP}/A_{H-V}$ ($A_H$) space, and therefore is an improvement upon simply relating $K_{DP}$ to the attenuation parameters with no knowledge of the DSD. We have assumed that at S-band $\delta$ is negligible. In operational terms the scheme assigns a value of $D_0$ to an entire rain shaft, thus fixing a linear relationship between $K_{DP}$ and $A_{H-V}$ which is unique to that particular core. The value of $N_0$ is not constrained and is allowed gate-to-gate variability through the rain shaft.

The values of total differential phase shift, $\phi_{DP}$, at S-band when there is attenuation occurring, are quite large. Goddard et al. (1994) propose a method of self-calibration of $Z_H$ to within 0.5 dB using the consistency of $Z_H$, $Z_{DR}$ and $K_{DP}$ in rain. This method has been used to calibrate $Z_H$ for the data in this study. It relies on the fact that $K_{DP}/Z_H$ as a function of $Z_{DR}$ is virtually independent of $\mu$ in the DSD. The technique involves adjusting the $Z_H$ calibration until the $\phi_{DP}$ calculated from the measured $Z_H$ and $Z_{DR}$ agrees with that observed. Provided the $\phi_{DP}$ used for calibration is limited to 30°, attenuation of $Z_H$ and $Z_{DR}$ is negligible and the method is reliable.
Figure 10. Fields along a ray showing the measured and attenuation corrected horizontally polarized backscatter reflectivity, $Z_H$, and differential reflectivity, $Z_{DR}$. Azimuth 269.6° at 19:36 GMT; gauge 7 is at a range of 32.2 km.

7. RESULTS AND VALIDATION

Figure 10 shows the fields of $Z_H$ and $Z_{DR}$ along the azimuth containing gauge 7 (see Fig. 2), which is situated at a range of 32.2 km. The measured $Z_{DR}$ shows negative values at the back of the storm of $-1.5$ dB, implying that the total amount of $A_{H-V}$ through the storm is 1.5 dB. The total amount of $A_{H}$ is impossible to ascertain by simple inspection, it can only be obtained by calculation. The attenuation is occurring over three major precipitation cores centres at 25, 50 and 65 km from Chilbolton, with the greatest amount $\sim 1$ dB occurring at the closest precipitation shaft where the temperature is about 20 °C (the temperature in Figs. 4 and 5). The correction to $Z_{DR}$ has, by definition, removed the negative values in the region of light precipitation (the negative values of $Z_{DR}$ between the radar and 20 km are caused by ground clutter). It is the corrected $Z_H$, $Z_{DR}$ pair values at each gate which are important for rainfall rate estimation. Only if both components are accurately corrected will the rainfall rate estimate be meaningful; this can be tested by using in situ raingauges and statistical methods.

(a) Raingauge

Over a single ray, validation using a raingauge can be beneficial, although raingauge/radar comparisons are fraught with difficulties, such as point representivity, beam overshoot and precipitation wind-drift. The correction algorithm can also only be truly validated if the raingauge is situated in a region affected by attenuation, and if the gauge has a rapid response time, because attenuation events are transitory. Gauge 7 was positioned in such a place at 1936 UTC; gauge 5 was between the radar and gauge 7, in the region causing the attenuation. Figure 11 shows the rainfall rate traces of gauges 5 and 7. Gauge 5 was recording 267 mm hr$^{-1}$ at the time of the coincidental plan position indicator (PPI)
scan; this was very close to the radar estimated $R$ (assuming that hail was not present in the precipitation volume), using both $Z_H (=58$ dBZ) and $Z_{DR} (=2.6$ dB) (DSD spectrum truncated at 10 mm), of 268 mm hr$^{-1}$, although it must be emphasised that at such high reflectivities the estimation of $R$ is very dependent upon the value of $\mu$ used within the DSD. There is evidence from the radar scan that hail is present in the immediate vicinity of gauge 5, resulting in spurious $R$ estimations using $Z_H$ and $Z_{DR}$. Regions of hail tend to give the radar signature of high $Z_H$ and low values of $Z_{DR}$ (Aydin et al. 1986), if the hail is tumbling i.e. appears to be anisotropic to the polarization radar. If the radar signature is interpreted as being due to rain in these high $Z_H$ low $Z_{DR}$ regions the rain DSD equivalent is a high number concentration of small raindrops. As rainfall rate is a volumetric effect then the result is a seemingly large value of $R$.

Using the uncorrected values of $Z_H$ and $Z_{DR}$ over the position of gauge 7 gives an estimated $R$ of 10 mm hr$^{-1}$ (using $\mu = 0$), whereas the corrected value of $R$ is 3.0 mm hr$^{-1}$. There is a seeming paradox here, in that the estimated rainfall rate has been reduced by correcting for attenuation. The reason for this is that the value of $Z_{DR}$ has been increased, which effectively reduces the number of small raindrops within the volume. This effect would not have occurred if $R$ had been estimated using $Z_H$ alone; the corrected and uncorrected values would have been 7.5 mm hr$^{-1}$ and 4.7 mm hr$^{-1}$ respectively. The corrected value of $R$ (3.0 mm hr$^{-1}$) is within 10% of the gauge 7 recorded rainfall rate of 3.3 mm hr$^{-1}$. On these results the attenuation correction algorithm appears to be effective.

Figure 11. Rainfall rates at gauges 5 and 7 during the time of the PPI shown in Fig. 2. The stars delimit the start and finish time of the PPI scan; the time resolution of the gauges is 10 seconds.
Using gauges to validate attenuation correction schemes has a limited scope, especially where rain gauges are sparsely distributed. A better means of validation would be to check for internal ‘self consistency’ within the scan. That is to compare regions affected by attenuation with those that are not, in terms of $Z_H$ and $Z_{DR}$. The scatterplots in Fig. 12 show remarkable detail as to the efficacy of the attenuation algorithm. The feature to note is the ‘bulge’ of negative $Z_{DR}$ in (b) which indicates the need for attenuation correction. This is most pronounced between 10 and 25 dBZ, and for the correction algorithm to be judged successful these negative values must not only be removed, but they must be adequately redistributed such that the corresponding values of $Z_H$ are reasonable. An attenuated azimuth is defined as a ray which contains negative $Z_{DR}$ (outside of the clutter region), and it includes the unattenuated portions of the ray between the radar and the attenuating core. Qualitatively comparing Fig. 12(a) and (c), that is the background (azimuths unaffected by attenuation) and corrected azimuths respectively, shows that the scheme does successfully correct for attenuation. The majority of the negative $Z_{DR}$ has been removed, all that remains is due to clutter similar to the pattern in (a). An interesting feature to note in Fig. 12(b) and (c) is the pairs of high $Z_H$ (>55 dBZ) and low $Z_{DR}$ (<2 dB), possibly being caused by hail. However it is only upon inspection of the scatterplot polynomials in Fig. 12(d) that the scheme can truly be shown to correct to a high degree of accuracy in the cases examined, for both $Z_H$ and $Z_{DR}$; this being the vital factor for rainfall rate estimation. The corrected polynomial results in a curve similar in shape and form to the background fit. The coefficients of the second-order polynomial fits provide a more quantitative compar-
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TABLE 3. COEFFICIENTS OF THE SECOND-ORDER POLYNOMIAL FITS SHOWN IN FIG. 12(d) FOR ZDR AS A FUNCTION OF $Z_H$.

Comparison between the separate data sets, shown in Table 3, the form of the polynomial being $a_0Z_H^2 + a_1Z_H + a_2$. Table 3 shows that all three curves are very similar in shape (the $a_0$ and $a_1$ terms), which is the result expected upon inspection of Fig. 12. The most important difference between the curves occurs in the constant $a_2$ term, which physically moves the fit to higher or lower values of $Z_{DR}$ for a constant $Z_H$. The corrected data-set constant term gives the closest match to the background value; the uncorrected $a_2$ is negative, this being indicative of the effects of attenuation. An exact match is not expected because of natural variation in the DSD throughout the PPI.

8. IMPLICATIONS FOR ATTENUATION CORRECTION AT C-BAND

Attenuation by rainfall is much larger at C-band than at S-band and, because most European and Japanese operational networks use C-band, the need for a method of correcting for attenuation at C-band is much more pressing. As a first step to exploring how the $K_{DP}/A_{H-V}$ S-band algorithm would function at C-band, Fig. 13 displays the relative contribution of different raindrop sizes to the various forward-scattering amplitudes for a Marshall and Palmer (1948) DSD with a rainfall rate of 100 mm hr$^{-1}$. If the curves were identically shaped then a single relationship would link $K_{DP}$ with $A_H$ as proposed by Bringi et al. (1990). At C-band the position of the peaks of the three curves are less consistent than at S-band; the $K_{DP}$ curves are similar for the two wavelengths, but the attenuation is weighted more towards larger drops at C-band compared with S-band. However, for drops larger than 6 mm the shapes of the C-band curves are more consistent. The sensitivity to $\mu$, the index in the gamma function, is far lower at C-band, as demonstrated by Fig. 14, showing that the $A_H$ versus $A_{H-V}$ curves for $\mu = 0$ and $\mu = 5$ are almost identical at C-band.

Ideally C-band polarization data should be used to assess the efficiency of the proposed correction scheme. Such data are not available to us, so our first step in assessing the efficiency of the correction algorithm at C-band was to use the S-band data to simulate attenuated C-band data. This was achieved by taking a ray of attenuated S-band data to ensure that appreciable attenuation is observed at C-band. The S-band data were first corrected for attenuation using the method outlined in section 6. S-band values of $Z_H$ and $Z_{DR}$ at each gate were then converted to C-band values, assuming the precipitation was rain; this involves calculating $N_0$ and $D_0$ at each gate using the standard technique of Seliga and Bringi (1976). If hail contaminates $Z_H$ and $Z_{DR}$ these $N_0$ and $D_0$ values will be spurious, but because both C- and S-band will both be contaminated, the C-band $Z_H$ and $Z_{DR}$ should be adequately simulated for our purpose.

However, in order to simulate the values of $A_H$, $K_{DP}$ and $\delta$ at C-band, only the regions where there was appreciable attenuation at S-band were used. The $N_0$ and $D_0$ values derived from the observed $A_{H-V}$, $K_{DP}$ at S-band were used to calculate these C-band parameters.
Figure 13. (a) Marshall and Palmer (1948) drop size distribution, DSD, for a rainfall rate of 100 mm hr\(^{-1}\); (b) Normalised imaginary part of the forward-scatter matrix in the horizontal at S- and C-band (indicative of \(A_{H}\)), weighted by the DSD shown in (a); (c) as (b) except indicative of \(A_{H-V}\); (d) as (b) except indicative of \(K_{DP}\). All at 0°C and \(R = 100\) mm hr\(^{-1}\) and values normalised by dividing by the maximum of the function. See text for further details.

Figure 14. S-band and C-band \(A_{H}\) as a function of \(A_{H-V}\) at 20°C for \(\mu = 0\) and \(\mu = 5\) in a normalised gamma drop size distribution. \(N_0 = 8000\) m\(^{-3}\) mm\(^{-1}\). See text for further details.
This should ensure that the calculated attenuation is only due to the rain component of the precipitation.

The predicted C-band data for the S-band data in Fig. 10 are displayed in Fig. 15. The $Z_{DR}$ behind the intense region of precipitation has reached $-5$ dB, which indicates that throughout the ray $5$ dB of differential attenuation has occurred (cf. $20$ dB of $A_H$). This compares with $1.5$ dB for the equivalent S-band ray shown in Fig. 10. Using the linear relationships proposed by Bringi et al. (1990) to act as a rough guide, $A_{H-V}$ at C-band should be a factor of four greater than at S-band. This implies that the values of negative C-band $Z_{DR}$ are of the correct order of magnitude.

The stimulated C-band $\phi_{DP}$ data show a change of greater than $100^\circ$ over a range of $4$ km. Another feature of note is the transient spike of $\delta$ occurring at a range of $30$ km which has a magnitude of $\sim +15^\circ$. Throughout the large differential phase shift region $\delta$ contributes to $\phi_{DP}$, it is only when the beam emerges from the intense precipitation core that the characteristic spike is observable. In practice $\phi_{DP}$ ray profiles at C-band tend to be noisier than this (Bringi et al. 1991).

There are difficulties in adjusting the scheme to cope with the addition of $\delta$, the largest problems occurring at the gates where the ray enters and subsequently emerges from the high $D_0$ rain shaft. (In the simulated dates shown in Fig. 15, $\delta$ adds a constant offset to $\phi_{DP}$; this is due to the value of $D_0$ being prescribed for the whole attenuating region by the scheme, which is perhaps unrealistic.) $K_{DP}$ at these gates is therefore spurious and, as a consequence, the weightings calculated using the value of $K_{DP}$ are incorrect throughout the attenuating rain shaft. The use of $K_{DP}$ and $A_{H-V}$ to calculate $A_H$ are also compromised; the result being that $A_H$ is hugely overestimated. The scheme, therefore, needs to be modified to cope with the significant contribution from $\delta$.

As there is a significant amount of random noise associated with the measurement of $\phi_{DP}$, it is necessary to smooth the $\phi_{DP}$ parameter so that $K_{DP}$ can be extracted. Within
the attenuation correction code a fourth-order Butterworth filter (Parks and Burns 1987) is utilized for this purpose, using a sampling rate of one tenth the original data. This filter can smooth out the jump in $\phi_{DP}$ at the entry and emergent range gates, and is also effective when a $\delta$ spike is present over a limited number of gates. This allows the weightings to be correctly assigned, but the actual values of $K_{DP}$, and hence the calculated values of $A_H$, are incorrect in this case where $\delta$ is adding a constant offset to $\phi_{DP}$.

The attenuation correction algorithm, therefore, needs to be modified for use at C-band. The step involving the weightings can still be used, but an alternative to using $K_{DP}$ and $A_{H-V}$ to calculate $N_0$ and $D_0$, and hence $A_H$, needs to be found.

The algorithm can be modified to accommodate the determination of $A_H$ when the $K_{DP}$ signal is contaminated by $\delta$ by using a look-up table to derive the $A_H$ from $A_{H-V}$ (Figure 6 suggests that there are not the problems in relating the two attenuation parameters to one another that there are in relating them to $K_{DP}$. The relationship between $A_H$ and $A_{H-V}$ should be relatively independent of $N_0$.)

Figure 14 shows that there is a dependency upon the value of $\mu$ in the DSD; the differences may not appear to be large but, as they add cumulatively along a ray, then an error of 0.2 dB km$^{-1}$ could result in an overall error in the estimation of $Z_H$ of 2 dBZ over a 10 km precipitation path length at C-band, and would clearly be worse for very extensive echoes. This error is quite small, though, when compared with the difference between the unattenuated C-band data and the corrected fields, shown in Fig. 16.

At this point a definition of terms is required. The unattenuated data relate to the C-band ray directly calculated from the corrected S-band $Z_H$ and $Z_{DR}$; these are used as ‘truth’ against which to test the attenuation correction schemes. The attenuated data relate to the same ray but with the calculated $A_H$ and $A_{H-V}$ subtracted from $Z_H$ and $Z_{DR}$ respectively; it is this ray which is used as the input to the C-band correction scheme. The attenuation corrected data are the output from the correction scheme.
The scheme, run without the modification to account for $\delta$ (dashed line in Fig. 16), shows an overestimation of 8 dBZ in the $Z_H$ field. This will lead to a serious overestimation of the rainfall rate in the regions behind the precipitation core which is causing the attenuation. When the look-up table modification is included, the algorithm gives values of $Z_H$ to within 1 dBZ of the unattenuated data, although there is a difference of $\sim$1 dB within the precipitation core suggesting that the distribution of the correction is not altogether accurate within this region.

If it is correct to assume that at C-band $A_H$ and $A_{H-V}$ are linearly related then the C-band algorithm could be quite simple. The values of total attenuation could be derived from the differential attenuation (i.e. negative $Z_{DR}$) observed behind the intense precipitation. This relies on the insensitivity of the $A_H - A_{H-V}$ relationship to changes in $\mu$ (Fig. 14).

In addition we note that the most severe cases of attenuation result from heavy rain having exceptionally large sized drops. Figure 9 shows that the values of $D_0$ are 3 or 4 mm, and lie along the curve for $N_0 = 800 \text{ m}^{-3} \text{ mm}^{-1}$. Comparison of Figs. 4 and 5 shows that for this value of $N_0$ the differential attenuation is about 75% of the horizontal attenuation. This suggests that if only one polarization is available for an operational radar then the vertical polarization would be preferable, because the attenuation would only be about one third of the value for horizontal polarization. The UKMO currently uses vertical polarization (Fair et al. 1990) but, as far as we can ascertain, is alone in this. Presumably horizontal polarization has generally been chosen because there is slightly less ground clutter for this polarization, as demonstrated by its predominantly negative values of differential reflectivity (Hall et al. 1984).

### 9. Conclusions

Previously, attenuation correction schemes have relied upon gate-by-gate iterative methods which quickly become unstable. These methods also rely upon backscatter parameters, such as $Z_H$ and $Z_{DR}$, which can become contaminated with hail within the volume. Hail is indistinguishable from rain when single parameter radar is used but should produce much less attenuation because of its low concentration. Therefore when hail is present the correction schemes may be needlessly implemented, resulting in overcorrection.

A new attenuation correction algorithm has been developed which makes use of the total amount of $A_{H-V}$ at the back of the storm, determined by the magnitude of the negative $Z_{DR}$ in the regions of light precipitation, and the measured $\phi_{DP}$. The scheme has been implemented at S-band and, using raingauge and statistical validation, found to accurately correct for attenuation. In this work it was assumed that the rain causing the attenuation was at 20 °C. Generally, because attenuation is temperature dependent, different look-up tables need to be generated for different temperatures. The advantages of the scheme are that it is numerically stable and relatively insensitive to hail. Simpler methods using $K_{DP}$ alone do not provide a unique solution. Ryzhkov and Zrnić (1994) observed a differential attenuation which was twice as much as that predicted from $K_{DP}$ by Bringi et al. (1990), and suggested that this was due to half-melted ice cores. The calculations and observation suggest that this higher attenuation for a given $K_{DP}$ is due to the larger raindrops, and that Bringi et al. (1990) underestimated the attenuation by limiting the maximum value of $D_0$ to 2.5 mm.

Implementation of the combined $\phi_{DP}$ $Z_{DR}$ technique at C-band is more difficult, because at this shorter wavelength there is more differential phase shift on backscatter by the large oblate raindrops. This backscatter phase shift is a transient superposed on the propagation phase, and makes the propagation component more difficult to estimate. However it
seems that a C-band the differential attenuation is more closely related to the total attenuation than at S-band. This suggests that a simpler algorithm may be implemented, in which the total attenuation is simply related to the total differential attenuation which is found from the magnitude of the negative $Z_{DR}$ in low intensity precipitation regions at greater range. It is suggested by these studies that this algorithm is not temperature dependent, because the ratio of total to differential attenuation varies little with temperature. Further work is needed to confirm this suggestion.

The implementation of polarization diversity involves the installation of a fast switch, so that pulses can be transmitted alternately with horizontal and vertical polarization. The implications for dwell time and scanning rates are discussed in Sachidananda and Zrnić (1985). In all these attenuation algorithms it is assumed that the radar beam is sampling at levels below the zero degree isotherm, and is in the rain or hail rather than the ice above the melting layer. Since nearly all severely attenuating storms occur in the summer this should not be too severe a restriction, but clearly it does place a limit on the absolute maximum range for the technique. Finally we note that if polarization diversity is not available, then it is preferable to use vertical polarization, as the attenuation is much reduced compared with that occurring in the horizontal.

ACKNOWLEDGEMENTS

This work was supported by the Natural Environmental Research Council ‘HYREX’ grant GST/02/718. We thank the Radio Communications Research Unit group at Rutherford Appleton Laboratory for allowing access to the Chilbolton radar. Jothiram Vivekennaden (National Center for Atmospheric Research) provided the scattering code.

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