

Polarimetric radar signatures of precipitation at S- and C-bands

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Abstract: Polarimetric radar measurements in precipitation at S- and C-band frequencies are considered. Time series data were obtained from three advanced radars: the National Center for Atmospheric Research (NCAR) CP-2 radar, the National Severe Storms Laboratory's (NSSL) Cimarron radar, and the C-band Poldirad radar operated by the German Aerospace Research Establishment (DLR). Measurements of radar reflectivity, differential reflectivity Z_{DR} , differential propagation phase ϕ_{DP} , and the crosscorrelation between horizontal and vertical polarised waves are derived from time series data in rain, rain mixed with ice, and in the stratiform ice phase of convective storms. Raindrops are modelled as oblate in shape with a gamma form for their size distribution. The gamma parameters (N_o , D_o , m) are varied over an entire range encompassing a wide variety of rainfall types. The radar rain measurements are shown to be in good general agreement with the model rain simulations. By combining Z_{DR} and ϕ_{DP} it is possible to identify regions of mixed particle types, e.g. raindrops and hail, or ice crystals and snowflakes. The differential phase upon backscatter may be identified by examining the range profile of ϕ_{DP} , giving additional clues as to the type and size of particles responsible for the backscatter.

1 Introduction

With the recent advent of sophisticated, polarimetric-based clutter characterisation methods, it is important to measure and model effectively the polarimetric backscatter and propagation effects of rainfall at typical microwave frequencies [1]. The raindrop size distribution (RSD) is governed by microphysical, thermodynamic and dynamical factors present in cloud systems. The RSD typically varies over orders of magnitudes both tempo-

rally and spatially; for example, spatial variability is found in the interior of cumulo-nimbus clouds and the stratiform anvil regions of large storm systems. It is also well known that microwave/millimetre waves are significantly affected by rainfall, and the extent of attenuation, for example, suffered by electromagnetic waves depends on the RSD and its variability in space and time. The rain medium also introduces significant differential attenuation and differential phase shift between the principal polarisation states (namely, horizontal (H) and vertical (V) polarisations) because the raindrops are oblate spheroidal in shape with a high degree of preferred orientation of their symmetry axis along the vertical direction. Additionally, the larger raindrops are uniformly more oblate than the smaller ones. A good review of these properties can be found in Reference 2. While a substantial body of literature exists on the propagation aspects of microwave/millimetre waves through rainfall, detailed modelling and experiments for different polarisation states is currently not available.

The use of advanced meteorological radars to characterise precipitation has reached a rather high level of sophistication only recently. The pioneering studies of McCormick, Hendry and their associates at the National Research Council of Canada have established the basis of polarimetric techniques, both for backscatter as well as forward scatter (propagation), using circular polarisation [3-6]. They have reported measurements of differential attenuation and differential phase shift in rain at K-, X- and S-bands, using the range profile of W/W_2 where W is the complex crosscovariance between the co- and cross-polar (simultaneously) received signals and W_2 is the conventional reflectivity. These studies have been extended [7-9] principally at S-band where differential phase shift is dominant with both absolute and differential attenuation being negligible.

The advent of pulse-to-pulse switching between H and V states and reception of copolar received signals through a single receiver system have advanced the accuracy to which the rain medium can be characterised [10, 11]. In addition, polarimetric techniques have found wide application in the detection of targets in clutter [12-14]. The technology of such polarimetric radar systems for meteorology has been reviewed by Bringi and Hendry [15], who also describe the main characteristics of 21 such radars existing worldwide. In this paper we present data from three advanced radars: the National Center for Atmospheric Research (NCAR) CP-2 radar located in Boulder, Colorado, USA, the National Severe Storm Laboratory's Cimarron radar located in Cimarron, Okla-

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homa, USA, and the C-band DLR radar located in Oberpfaffenhofen, Federal Republic of Germany. The main characteristics of the CP-2 and Cimarron radars are described in Reference 15 while the DLR radar is described in detail in Reference 16. Table 1, adapted from Reference 15 gives the salient features of these radar systems.

where σ_{HH} , σ_{VV} are the radar cross-sections at H and V states, respectively, and $N(D)$ is the particle size distribution. The wavelength is λ , while $K = (\epsilon_r - 1)/(\epsilon_r + 2)$, ϵ_r being the complex permittivity of the particle. The differential reflectivity Z_{DR} is defined as [10]

$$Z_{DR} = 10 \log (Z_{HH}/Z_{VV}) \text{ dB} \quad (2)$$

Table 1: Main characteristics of the CP-2, Cimarron and Poldirad radars, adapted from Reference 15

Characteristic	CP-2	Cimarron	Poldirad
location	Boulder, CO, USA	Cimarron, Oklahoma, USA	Oberpfaffenhofen, Federal Republic of Germany
wavelength, cm	10.7	10.7	5.3
peak power, kW	1200	500	500
pulse length, μ s	1	1	0.5, 1.0, 2.0
PRF, s^{-1}	typically 1000	1300	490, 1200, 2400
antenna type	centre-fed paraboloid	centre-fed paraboloid	offset-fed paraboloid
beam width, deg.	0.93	0.9	1
polarisations, radiated	H or V	H or V	any elliptical, 3° increments in orientation of ellipse
polarisations, received	copolar to transmit state	copolar to transmit state	copolar and crosspolar to transmit state
Doppler capability	yes	yes	yes
range resolution, m	typically 200	150	75, 150, 300

The backscattered signals received by a radar have two primary features: (a) parameters that are range cumulative, and (b) variabilities that are functions of the backscatter properties of the medium. The range-cumulative features are functions of the forward-scatter properties of the raindrops whereas individual gate features are functions of the backscatter properties. These effects are not easily separable. Circular polarisation techniques have been used to separate out these effects, especially under propagation-dominated conditions [17]. In Reference 17 pulse-to-pulse switching between RHC and LHC states was not used, rather the transmitted pulse was RHC, the received wave being decomposed into its RHC and LHC components. Our techniques differ somewhat in that we employ pulse-to-pulse switching between H and V states (or orthogonal linear states) with coherent, copolar receptions through the same receiver and processor system.

This paper presents a study of several polarimetric observations of precipitation. The measurements analysed are as follows:

- radar reflectivity
- differential reflectivity between H and V polarisations
- differential propagation phase between H and V polarisations
- differential phase shift on backscatter and
- crosscorrelation between the H and V polarised signals.

2 Polarimetric radar parameters

Using a horizontal/vertical polarisation basis, we define the copolar radar reflectivities Z_{HH} and Z_{VV} as

$$Z_{HH} = \frac{\lambda^4}{\pi^5 |K|^2} \int \sigma_{HH}(D) N(D) dD \text{ mm}^6 \text{ m}^{-3} \quad (1a)$$

$$Z_{VV} = \frac{\lambda^4}{\pi^5 |K|^2} \int \sigma_{VV}(D) N(D) dD \text{ mm}^6 \text{ m}^{-3} \quad (1b)$$

It is conventional to express the radar reflectivities in dBZ relative to $1 \text{ mm}^6 \text{ m}^{-3}$, i.e. $10 \log (Z_{HH})$.

If S_{HH} , S_{VV} are the backscatter amplitudes at H and V states, then the crosscorrelation coefficient ρ_{HV} can be defined as

$$\rho_{HV} = \frac{\int S_{HH}(D) S_{VV}^*(D) N(D) dD}{\{[\int |S_{HH}|^2 N(D) dD][\int |S_{VV}|^2 N(D) dD]\}^{1/2}} \quad (3)$$

We further define $\rho_{HV} = \rho_{HV}(0) \exp(j\delta)$ where $\rho_{HV}(0)$ is the magnitude and δ the differential phase shift on backscatter. An explained later in Section 3, the '0' in brackets refers to zero time lag in radar systems using pulse-to-pulse switching between the transmitted H and V states.

If $f_{HH}(D)$ and $f_{VV}(D)$ are the forward-scatter amplitudes then the specific differential phase K_{DP} is defined as

$$K_{DP} = \frac{2\pi}{k_o} \text{Re} \int [f_{HH}(D) - f_{VV}(D)] N(D) dD \text{ } ^\circ \text{km}^{-1} \quad (4)$$

where k_o is the free-space propagation constant. The two-way differential propagation phase between ranges r_1 and r_2 can be written as

$$\phi_{DP} = 2 \int_{r_1}^{r_2} K_{DP}(r) dr \text{ degrees} \quad (5)$$

Instead of choosing an H/V basis, it is possible to choose a linear polarised basis, where the unit polarisation vectors are aligned at angles α and $\alpha + \pi/2$ relative to the H-direction. Thus, $Z_{DR}(\alpha)$ can be defined as the ratio (in decibels) between the copolar reflectivities at the two polarisation states defined by α and $\alpha + \pi/2$. Similarly, we can define $\phi_{DP}(\alpha)$ and $\rho(\alpha)$ as the differential propagation phase and crosscorrelation coefficient, respectively, between the two polarisation states defined by α and $\alpha + \pi/2$.

2.1 Raindrops

Microphysical properties of the rain medium that are important for radar observations are the raindrop size, shape and orientation distributions. The size distribution

$N(D)$ may be modelled as a gamma distribution of the form [18]

$$N(D) = N_o D^m \exp[-(3.67 + m)D/D_o] \quad \text{m}^{-3} \text{mm}^{-1} \quad (6)$$

where $N(D)$ is the number of raindrops per unit volume per unit size interval D to $D + \Delta D$. Note that D refers to the equivalent spherical diameter, whereas D_o is the median volume diameter. Drops larger than D_o contribute to half the total rain-water content. Together with N_o and m the gamma distribution is characterised by three parameters whose physical variability is given in Reference 18, e.g. N_o varies between 200 and 2×10^4 ($\text{m}^{-3} \text{mm}^{-1-m}$), D_o between 0.5 and 2.5 mm, and m between 0 and 5. These parameter ranges reflect RSD variability found in differing storm types found worldwide [18].

The equilibrium shape of raindrops at terminal fall speed is that shape for which the forces due to surface tension, hydrostatic pressure and aerodynamic pressure (due to airflow around the drop) are in balance [19]. An approximation for the shape of large raindrops as oblate spheroidal with axis ratio (ratio of minor to major axis, a/b) decreasing uniformly with increasing D is given in Reference 20. Recently, highly accurate computations of the shapes of large raindrops have been performed [21]. In this paper, however, we use the simpler analytical solution for a/b against D (with D in centimetres) derived in Reference 19:

$$a/b = 1.03 - 0.62D \quad (7)$$

The orientation of raindrops has been studied theoretically to show that the mean canting should be close to zero with standard deviation of the order of a few degrees [22]. These deductions are in good agreement with the observations of the canting-angle distributions of raindrops using linear and circular polarisation measurements [6]. In this paper we assume that the raindrops are equi-oriented with the minor axis of the oblate spheroid being vertical [23].

It is well known that in the Rayleigh limit Z_{HH} is related to the sixth moment of the RSD, while Z_{DR} is related to the reflectivity-weighted mean axis ratio of the raindrops filling the radar resolution volume. Because the mean axis ratio can be related to a mean size, Z_{DR} is a monotonic function of the reflectivity-weighted mean drop size [24]. In Reference 36 it is shown from theoretical considerations that $\rho_{HV}(0) > 0.99$ at S-band even in intense rain. In the Rayleigh limit, $\delta = 0^\circ$; however, at higher frequencies (Mie region) δ can be quite significant. Note that Z_{HH} , Z_{DR} , $\rho_{HV}(0)$ and δ depend on the backscatter properties of the rain medium. At long wavelengths K_{DP} is related to the mass-weighted (i.e. D^3 weighted) mean axis ratio of the raindrops [26]. Equivalently, K_{DP} is nearly related to the D^4 th moment of the RSD since axis ratio and D are related.

The raindrop model is now used to simulate the radar parameters defined in eqns. 1-4 at S- and C-bands. For each triplet of parameters (N_o , D_o , m) we calculate the various radar observables using the previously defined shape and orientation assumptions. The parameters of the gamma RSD are then varied over the entire range prescribed in Reference 18 so that a scatter plot is generated, the scatter being representative of natural RSD fluctuations. Figs. 1-4 show the results of our simulations, the corresponding frequency band being denoted by S or C attached to the radar observables. Figs. 1a and b show

Z_{DR} against Z_{HH} at S- and C-band, respectively. At $Z_{HH}(S) = 50$ dBZ, $Z_{DR}(S)$ varies between 1.5 and 3 dB, while at C-band $Z_{DR}(C)$ varies between 1.5 and 4 dB. These Z_{DR} variations at a fixed reflectivity level reflect the physical variability of the parameters m and D_o of the gamma RSD.

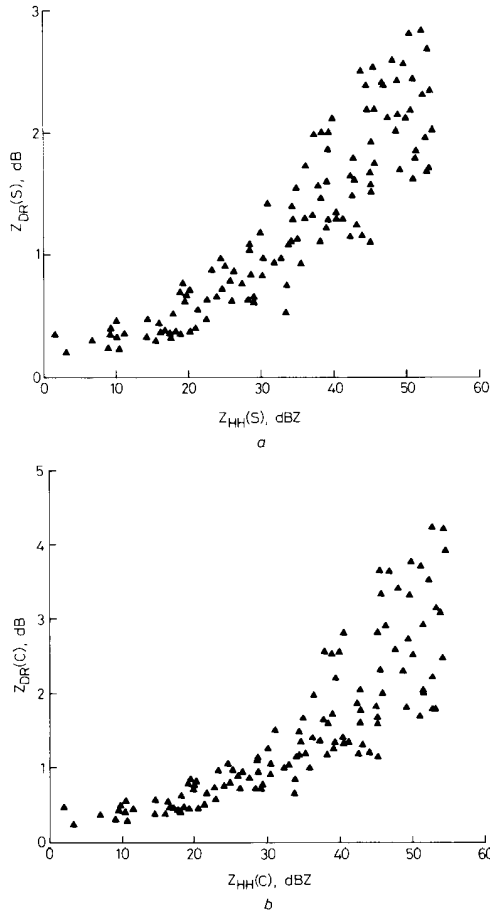


Fig. 1 Computations of Z_{DR} against Z_{HH} for oblate raindrops assuming a gamma size distribution

Each data point refers to a particular value of the triplet of gamma parameters (N_o , D_o , m). The scatter of the data reflects a wide variety of rainfall types
a S-band (10 GHz) b C-band (5.5 GHz)

Figs. 2a and b show K_{DP} against Z_{HH} at S- and C-band, respectively. At $Z_{HH} = 50$ dBZ, $K_{DP}(S)$ varies between 1.5 and 2°km^{-1} whereas $K_{DP}(C)$ varies between 2 and 4°km^{-1} . As is well known, this causes depolarisation of circularly polarised waves even at long wavelengths [7, 8]. With intense rain rates and the possibility of long propagation paths, the use of circular polarisation for radars with only crosspolar reception (i.e. transmit RHC, receive LHC) must be avoided.

Fig. 3 shows $\rho_{HV}(0)$ against $Z_{HH}(S)$ and $\rho_{HV}(0)$ against $Z_{DR}(C)$. The various factors which contribute to $\rho_{HV}(0)$ deviating from unity are discussed in Reference 27. Principal among these are non-zero values of δ and/or mixed phase precipitation, i.e. rain mixed with partially melting ice or hail. At C-band large raindrops contribute substantially to δ as shown in Fig. 4.

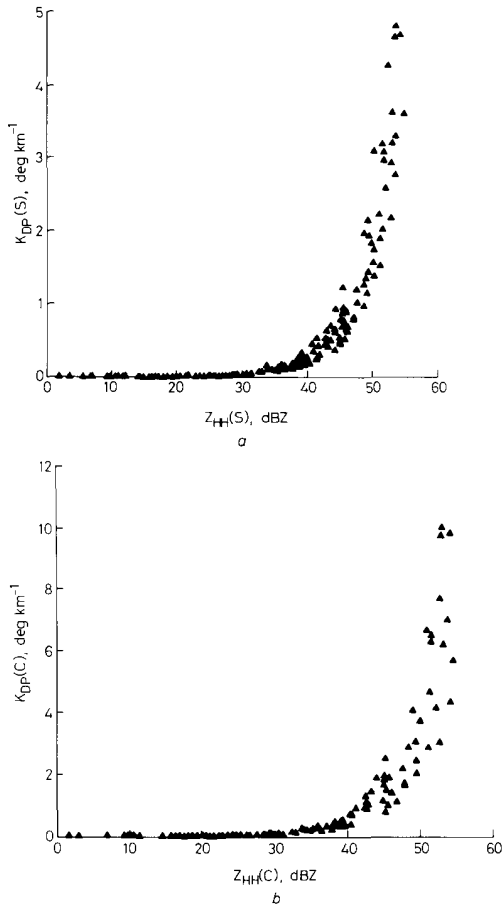


Fig. 2 Computations of K_{DP} against Z_{HH} for oblate raindrops assuming a gamma size distribution
 Each data point refers to a particular value of the triplet of gamma parameters (N_0, D_0, m). The scatter of the data reflects a wide variety of rainfall types
 a S-band b C-band

2.2 Ice

The radar parameters defined earlier are dependent on the distributions of size, shape, orientation, and dielectric constant of the particles filling the radar resolution volume. For raindrops these distributions are well known but for a large variety of ice particles they are highly variable and thus assumptions must be made, particularly with respect to shape, orientation and composition of the ice particles. The melting of ice particles into raindrops has been modelled using a coupled radar-cum-melting model in References 28 and 29, while in Reference 30 models for estimating rain and hail rates in mixed-phase precipitation using Z_{HH} , Z_{DR} , and K_{DP} have been developed. The general shapes used for ice particles are either conical or spheroidal, the extreme oblate-prolate shapes being used for ice crystals (columns, needles or plates). The fall mode behaviour can be quite complex but often modelled as Gaussian or simple harmonic with the symmetry axes aligned in a mean sense along the vertical or horizontal directions. It is not the intent here to review the large amount of literature existing in the cloud physics or radar areas but we refer to the general References 2 and 31.

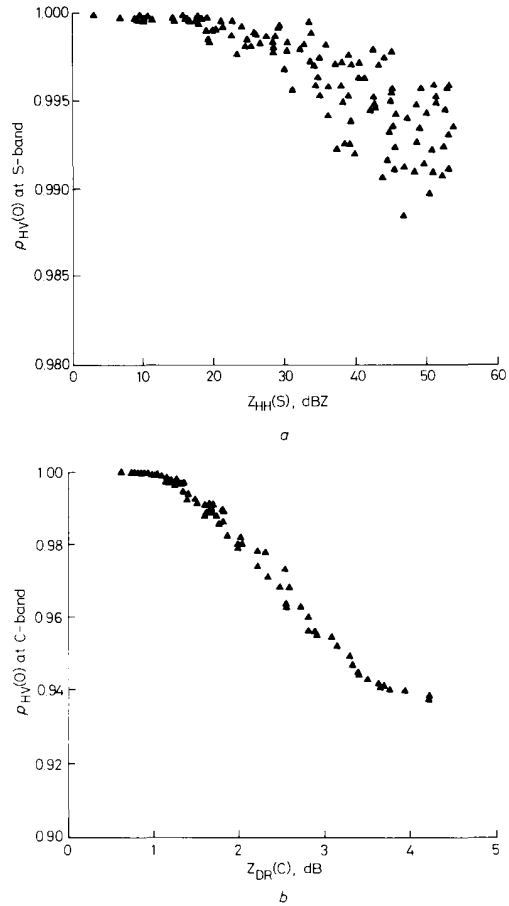


Fig. 3 Computations of $\rho_{HV}(0)$ for oblate raindrops assuming a gamma size distribution
 Each data point refers to a particular value of the triplet of gamma parameters (N_0, D_0, m). The scatter of the data reflects a wide variety of rainfall types
 a $\rho_{HV}(0)$ against $Z_{HH}(S)$ at S-band
 b $\rho_{HV}(0)$ against $Z_{DR}(C)$ at C-band

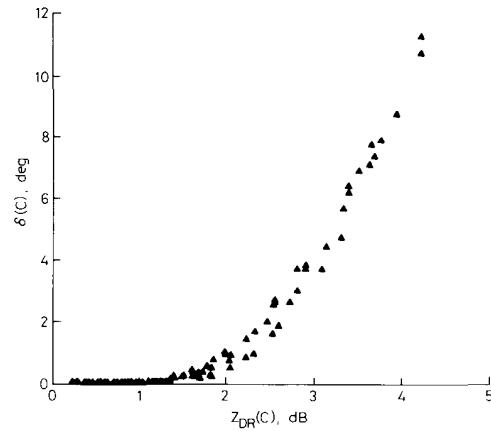


Fig. 4 Computations of δ against $Z_{DR}(C)$ for oblate raindrops assuming a gamma size distribution
 Each data point refers to a particular value of the triplet of gamma parameters (N_0, D_0, m). The scatter of the data reflects a wide variety of rainfall types

3 Polarimetric radar techniques

Full polarimetric capability implies polarisation diversity on transmission and reception [12]. The NCAR CP-2 radar is a dual-frequency (S-/X-bands) radar which can measure Z_{DR} and ϕ_{DP} at S-band using pulse-to-pulse switching of the transmitted polarisation between H and V states. In addition, the ratio of reflectivities at S- and X-bands can be measured. The Cimarron radar operated by the National Severe Storms Laboratory (NSSL) is also equipped for Z_{DR} and ϕ_{DP} at S-band using pulse-to-pulse switching. The C-band Poldirad radar operated by the German Aerospace Research Establishment (DLR) possesses full polarimetric capability, i.e. pulse-to-pulse switching between orthogonal states with corresponding dual-channel reception [16, 23]. Unless specified otherwise, we utilise only a subset of this measurement capability, i.e. switching between H and V states with copolar reception through the same receiver and processor. A brief description of these 3 radars is provided in Table 1 (see also Reference 15).

The measurement of Z_{DR} and ϕ_{DP} as well as the first three moments of the Doppler spectrum when a pulsed Doppler radar is used for transmitting alternately polarized H and V pulses, with coherent reception of the copolar signals through the same receiver system, is discussed by Sachidananda and Zrnic [32]. Their algorithm for ϕ_{DP} is based on Reference 33. If H_{2n} , V_{2n+1} represent the sample voltages at a fixed range delay r due to H and V transmitted pulses, respectively, then Z_{DR} can be estimated from the mean sample powers \hat{P}_{HH} and \hat{P}_{VV} , where

$$\hat{P}_{HH} = \frac{1}{M} \sum_{i=0}^{M-1} |H_{2i}|^2 \quad (8a)$$

$$\hat{P}_{VV} = \frac{1}{M} \sum_{i=0}^{M-1} |V_{2i+1}|^2 \quad (8b)$$

$$\hat{Z}_{DR} = 10 \log (\hat{P}_{HH}/\hat{P}_{VV}) \quad (8c)$$

and M is the number of H/V sample pairs.

The estimate for ϕ_{DP} from Reference 33 is

$$\hat{\phi}_{DP} = \frac{1}{2} \arg (\hat{R}_a \hat{R}_b^*) \quad (9)$$

where

$$\hat{R}_a(T_S) = \frac{1}{M} \sum_{i=0}^{M-1} H_{2i}^* V_{2i+1} \quad (10a)$$

$$\hat{R}_b(T_S) = \frac{1}{M} \sum_{i=0}^{M-1} V_{2i+1}^* H_{2i+2} \quad (10b)$$

T_S being the pulse repetition time.

$\hat{\phi}_{DP}$ at two ranges r_1 and r_2 can be used to calculate the specific differential phase shift as

$$K_{DP} = \frac{\hat{\phi}_{DP}(r_2) - \hat{\phi}_{DP}(r_1)}{2(r_2 - r_1)} \quad (11)$$

The crosscorrelation coefficient $\hat{\rho}_{HV}(0)$ at zero time lag is obtained from Reference 32:

$$\hat{\rho}_{HV}(0) = |\hat{\rho}_{HV}(T_S)/\hat{\rho}(T_S)| \quad (12a)$$

where

$$\hat{\rho}_{HV}(T_S) = \frac{|\hat{R}_a(T_S)| + |\hat{R}_b(T_S)|}{2(\hat{P}_{HH} \hat{P}_{VV})^{1/2}} \quad (12b)$$

and $\hat{\rho}(T_S)$ is the autocorrelation estimate of the H-polarised signals. This estimate is obtained by assuming a Gaussian Doppler spectrum for which $|\hat{\rho}(T_S)| = |\hat{\rho}(2T_S)|^{1/4}$. Note that $\hat{\rho}(2T_S)$ is obtained directly from the H- or V-polarised signals.

To meaningfully compare radar data with model computations, the statistical fluctuations in the radar measurements must be reduced to a level smaller than the physical variabilities. Statistical fluctuations have been studied for the first three moments of the Doppler spectrum [34]. The standard errors quoted assume that the Doppler spectrum width is in the range $1-4 \text{ ms}^{-1}$, that the number of sample pairs is 100-200, that the mean $\rho_{HV}(0)$ is 0.99-0.995 and that SNR > 20 dB. The zeroth moment corresponding to the conventional reflectivity can be estimated with a standard error of 1 dB. \hat{Z}_{DR} can typically be estimated to within 0.1-0.2 dB [35, 36]. $\hat{\phi}_{DP}$ errors have been studied by Sachidananda and Zrnic [25], who show theoretically that the standard error in $\hat{\phi}_{DP}$ is the order of a few degrees. The errors in \hat{Z}_{DR} , $\hat{\phi}_{DP}$ and $\hat{\rho}_{HV}(0)$ are very sensitive to SNR and the mean value of $\rho_{HV}(0)$. These standard errors are applicable to data from a single resolution volume, with further reduction made possible by averaging (filtering) contiguous range gates.

The estimation of K_{DP} is based on the range profile of ϕ_{DP} . A third-order nondecreasing polynomial fit to the ϕ_{DP} range profile is one method used to estimate K_{DP} at each resolution volume. We also perform range filtering on the various radar observables based on infinite impulse response (IIR) digital filters. To estimate K_{DP} , for example, the range profile of ϕ_{DP} would be digitally filtered to suppress the 'high frequency' range gate-to-range fluctuations while still preserving the mean trend with range. This procedure significantly decreases the standard error in K_{DP} to typically around $0.4 \text{ }^\circ\text{km}^{-1}$.

4 Radar measurements

4.1 CP-2 radar

We first present radar data obtained with the NCAR CP-2 radar which was located near Boulder, Colorado, USA during the summer of 1987. The radar was operated in a special time series mode for brief periods of time. The transmitted wave's polarisation state was switched between H and V states on alternate pulses while the received signal was always copolar to that transmitted. Range profiles of Z_{HH} , Z_{DR} , ϕ_{DP} and $\rho_{HV}(0)$ were generated using techniques described in Section 3. Figs. 5a and b show a typical range profile through an intense convective storm at low elevation angle. In the range interval 92 to 98 km the following can be deduced, (i) average $K_{DP} = 2.8 \text{ }^\circ\text{km}^{-1}$, (ii) $Z_{HH}(S) > 55 \text{ dBZ}$, (iii) average $Z_{DR} \approx 1.5 \text{ dB}$ and (iv) $\rho_{HV}(0) \leq 0.90$. From Fig. 1a we can ascertain that for $Z_H = 55 \text{ dBZ}$ the corresponding Z_{DR} for a pure rain medium would be in the range 1.75-3.00 dB while $\rho_{HV}(0) > 0.99$. Thus, in the example at hand we can infer that mixed phase precipitation is occurring in the range interval 92-98 km, most probably intense rain mixed with hail. Using the relation $R = 40.5(K_{DP})^{0.85}$ gives a rain rate of 97 mm hr^{-1} with $K_{DP}(S) = 2.8 \text{ }^\circ\text{km}^{-1}$ [37]. To derive the rain rate we assume that the hail particles are quasi-spherical and tumble giving $f_{HH} \approx f_{VV}$ [30]. Thus, they will not contribute to K_{DP} whereas the raindrops will (see Reference 4).

We accumulated a large number of range profiles through convective rainshafts from several different storms during the summer of 1987. Care was taken to

exclude mixed-phase precipitation by eliminating data with low values of $\rho_{HV}(0)$ or where the dual-frequency (S- to X-band) reflectivity ratio (or hail signal) exceeded

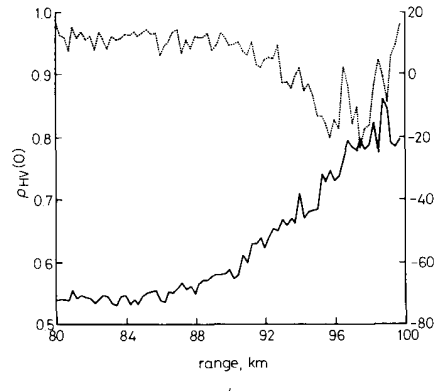
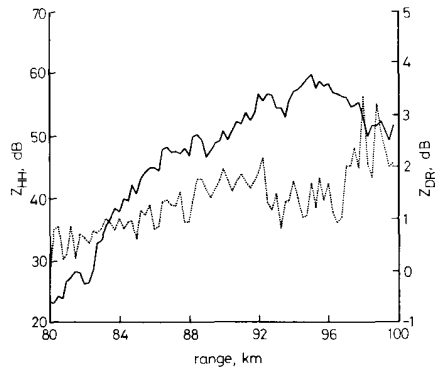


Fig. 5 Range profile of radar measurements obtained using the NCAR CP-2 radar at low elevation angle through a convective storm
29th July 1987; 20 : 38; azimuth = 125; elevation = 1.0
a Z_{HH} and Z_{DR} : — reflectivity, differential reflectivity
b $\rho_{HV}(0)$ and $\phi_{DP}(0)$: — propagation differential phase, zero-lag cross-correlation

3 dB. The Z_{HH} and Z_{DR} fields were filtered in range using a weighted, moving-average filter. A scatterplot of $Z_{DR}(S)$ against $Z_{HH}(S)$ was constructed from this fairly large database and is shown in Fig. 6a. This plot can be compared with Fig. 1a. For convenience, the two dashed curves shown in Fig. 6a were obtained from Fig. 1a as the upper and lower bounds in Z_{DR} for a given Z_{HH} . It is clear that the measurements fall within the bounds based on RSD fluctuations.

Fig. 6b shows the average value of $\rho_{HV}(0)$ against $Z_{HH}(S)$, the average being done over 1 dB categories of Z_{HH} . The database is the same as that used in Fig. 6a. The vertical bars denote the standard deviation. The dashed curve is the mean relationship drawn by eye from Fig. 3a. The radar measurements are thus seen to be in good agreement with the RSD simulations. Note that the RSD simulations of $\rho_{HV}(0)$ account for variable raindrop size distributions as well as the mean relationship between axis ratio and size, see eqns. 6 and 7.

Fig. 7 shows range profiles of (a) $Z_{HH}(S)$, (b) $Z_{DR}(S)$ and (c) $\phi_{DP}(S)$ through the ice phase of a convective storm at high elevation angle. The convective core is

located in the range interval 20–40 km, i.e. high reflectivity. Beyond 40 km the profile penetrates through the (low reflectivity) stratiform anvil region of the storm. An

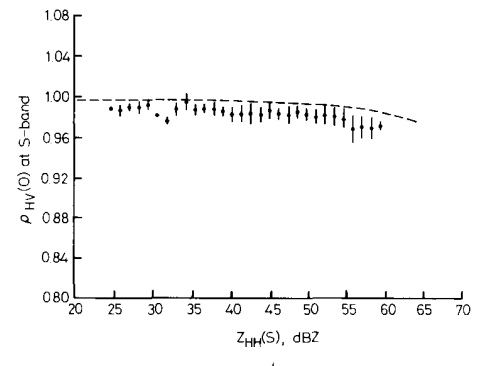
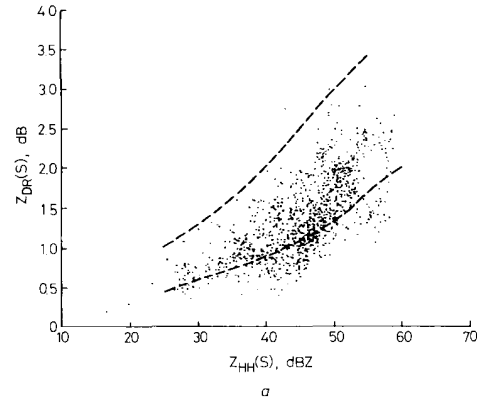


Fig. 6 $Z_{DR}(S)$ and $\rho_{HV}(0)$ for data taken in convective rainfall using the CP-2 radar

a Scatterplot of radar measured $Z_{DR}(S)$ against $Z_{HH}(S)$. Dashed lines are drawn in as the upper and lower bounds from the data of Fig. 1a
b Radar measured $\rho_{HV}(0)$ against $Z_{HH}(S)$. The averaging is done over 1 dB categories of Z_{HH} . Vertical lines represent the standard deviation. The dashed line is drawn in as the mean fit (by eye) to the calculations shown in Fig. 3a

average K_{DP} of 0.6 km^{-1} is estimated in the stratiform region (40–60 km). Oriented ice crystals of the plate type can give such large K_{DP} values [17]. Because Z_{DR} is low in this region (0–0.5 dB) we hypothesize that larger snowflakes which are quasi-spherical and tumble are mixed in with the oriented crystals. Again, they do not contribute to K_{DP} because these particles have $f_{HH} \approx f_{VV}$, while the oriented plate-type crystals do contribute to K_{DP} via $f_{HH} - f_{VV}$ in eqn. 4. Since Z_{DR} is a measure of the reflectivity-weighted mean shape of the mixed-phase precipitation, it is biased towards 0 dB by the larger, quasi-spherical snowflakes whose $\sigma_{HH} \approx \sigma_{VV}$.

4.2 Cimarron Radar

We now present radar measurements using the NSSL S-band Cimarron radar located NW of Oklahoma City, Oklahoma, USA. This radar was operated in a special time series mode for brief periods of time during the Spring of 1989. Data from this radar have been reported earlier by [25, 30]. A high-power polarisation switch was used to transmit alternately H- and V-polarised pulses, the received signal being always copolar

to that transmitted. Thus, range profiles similar to Fig. 5 could be generated from the time series data. Figs. 8 and 9 show examples through an intense convective storm at

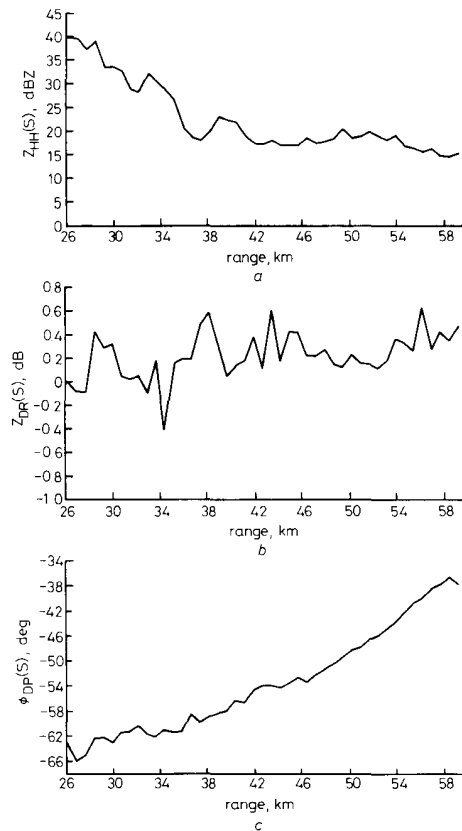


Fig. 7 Range profile of CP-2 radar measurements taken at high elevation angle through the ice phase of convective and stratiform parts of a storm

The convective core is located between ranges 20 and 40 km. The stratiform part extends beyond 40 km.

a $Z_{HH}(S)$
b $Z_{DR}(S)$
c $\phi_{DP}(S)$

a low elevation angle of 0.5° . Fig. 8a shows Z_{HH} and Z_{DR} against range while Fig. 8b shows ϕ_{DP} and $\rho_{HV}(0)$ against range. The sharp increase in ϕ_{DP} in the range 38–50 km is noteworthy. In the range interval 42–49 km, Z_{DR} is in the range 1–1.5 dB, while Z_{HH} is in the range 55–60 dBZ. Thus, this case is similar to Fig. 5 in that intense rain mixed with hail is occurring in the range 42–49 km. Fig. 9 shows the IIR filtered version of ϕ_{DP} . This filters out the ‘high frequency’ gate-to-gate variations while still preserving the mean trend with range. Fig. 9 also shows the mean Doppler velocity against range. The mean Doppler velocity is obtained by combining eqns. 10a and 10b as suggested by Sachidananda and Zrnica [32]. In the intense precipitation shaft (42–49 km) the K_{DP} peaks to around 4°km^{-1} or a rain rate of 132 mm hr^{-1} . The mean radial velocity profile shows a sharp transition from -12 ms^{-1} at 43 km to $+12\text{ ms}^{-1}$ at 49 km. Negative (positive) radial velocities represent winds toward (away from) the radar. Thus, the intense precipitation at the surface coincides with a region of strong radial diver-

gence of the wind. This signature is referred to as a microburst which causes damaging winds at the surface.

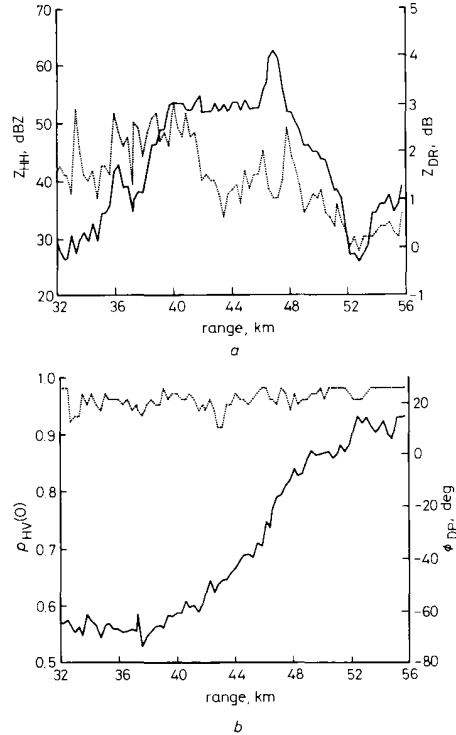


Fig. 8 Range profile at S-band of Cimarron radar measurements taken at low elevation angle through an intense storm

6th June 1989; 14:34:31; azimuth = 285; elevation = 0.5°

a Z_{HH} and Z_{DR} : — reflectivity, differential reflectivity
b ϕ_{DP} and $\rho_{HV}(0)$: — propagation differential phase, zero-lag cross-correlation

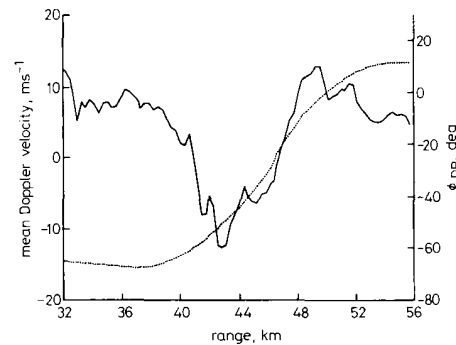


Fig. 9 An IIR digital filter is applied to the ϕ_{DP} data of Fig. 8b to filter out the ‘high frequency’ range gate-to-range gate variations, while still retaining the mean increasing trend with range. Also shown is the mean Doppler velocity profile corresponding to a downburst case

The precipitation shaft is collocated with a strong, vertically directed downdraft which diverges radially near the surface [38].

Fig. 10 shows an example of a range profile through the stratiform anvil region of a mesoscale convective complex. The reflectivity ‘bright band’ is located near 33–35 km where a peak in Z_{DR} of 1.2 dB is noted. Beyond

the 'bright band' the reflectivity falls off rapidly while at the same time ϕ_{DP} shows a monotonic increasing trend with range, see Fig. 10b. At the 'bright band' $\rho_{HV}(0)$

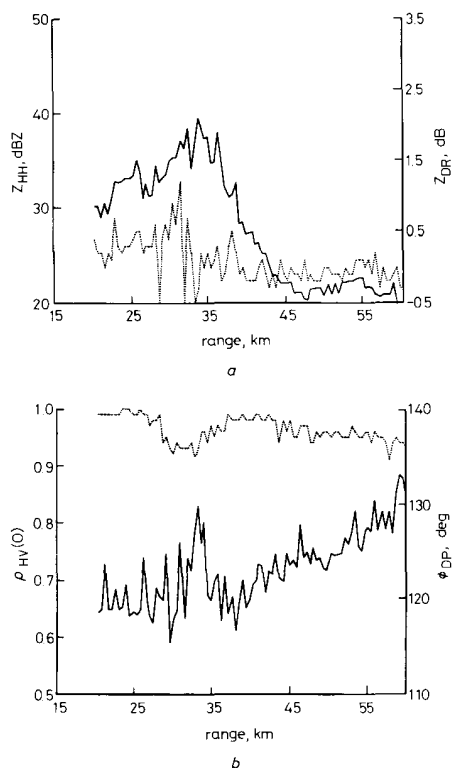


Fig. 10 Range profile of Cimarron radar measurements through the 'bright band' of a stratiform anvil region of a mesoscale convective system
3rd June 1989; 21:08; azimuth = 28; elevation = 4.9
The 'bright band' is located in the range 33–35 km
a Z_{HH} and Z_{DR} ; — reflectivity, differential reflectivity
b ϕ_{DP} and $\rho_{HV}(0)$; — propagation differential phase, zero-lag crosscorrelation

shows a minima of around 0.9. Significant deviation of $\rho_{HV}(0)$ from unity occurs in the interval 29–33 km. In this same region ϕ_{DP} fluctuations are larger and near 33 km a 'bump' in ϕ_{DP} above the mean trend is noticed. If $\delta = 0^\circ$, then eqn. 9 gives the true differential propagation phase. However, if δ is non-zero then eqn. 9 gives the profile of $(\phi_{DP} + \delta)$, where ϕ_{DP} is the range cumulative part and δ is the backscatter differential phase at a particular range location. In practice, it is difficult to separate out the two components. In this particular example, a mean ϕ_{DP} trend with range can be identified and a peak $\delta \approx 10^\circ$ may be estimated in the 'bright band'. The 'bright band' is known to consist typically of large, melting snowflakes, ice crystals and small raindrops. We believe that nonzero δ causes the sharp reduction of $\rho_{HV}(0)$ near the 'bright band' (see also Reference 39). In the range interval 40–60 km, a mean $K_{DP} \approx 0.25^\circ \text{km}^{-1}$ may be deduced. As discussed earlier in reference to Fig. 7, we infer that this K_{DP} is caused by oriented, plate-type ice crystals mixed with larger, quasi-spherical snowflakes. Mixed-phase precipitation is inferred since $Z_{DR} \approx 0$ dB in this range interval. The decrease in $\rho_{HV}(0)$ with range beyond 45 km is most probably due to low signal-to-noise ratio.

4.3 Poldirad

The German Aerospace Research Establishment (DLR) operates an advanced C-band polarimetric radar called Poldirad. This radar is located near Munich, Germany. A good technical description of the radar and examples of data taken in convective and stratiform conditions are given in Reference 16.

In the fast-switching time series mode, the polarisation state of the transmitted wave is switched alternately between any two selected orthogonal states on a pulse-to-pulse basis. We have selected the H/V states. For each transmit pulse, the inphase and quadrature-phase components of the copolar and crosspolar receive signals are recorded. Only the copolar time series data are used here to estimate ϕ_{DP} and $\rho_{HV}(0)$ as in eqns. 9 and 12. Fig. 11 shows an example of a range profile through a convective cell at an elevation angle of 2.1° . These data were gathered on 23rd August, 1988. Fig. 11a shows the reflectivity and Z_{DR} profile, and Fig. 11b shows the profiles of ϕ_{DP} and $\rho_{HV}(0)$. Note the steady increase of ϕ_{DP} with range characteristic of propagation differential phase in rainfall. Z_{DR} typically lies in the range 0–3.5 dB. The standard error of ϕ_{DP} was estimated from the time series data to be in the range $2\text{--}4^\circ$ when $\rho_{HV}(0) > 0.95$ and 64 pairs of H/V samples are used, i.e. $M = 64$ in eqns. 9 and 10. Fig. 11b shows an IIR filter applied to the ϕ_{DP} data which is shown by the dashed line which effectively filters out the high-frequency range gate-to-range gate variations, yet preserving the mean trend with range. K_{DP} values determined from the filtered ϕ_{DP} data were in the range $0\text{--}2^\circ \text{km}^{-1}$. These radar measurements can be compared to the C-band rainfall simulations shown in Figs. 1–4.

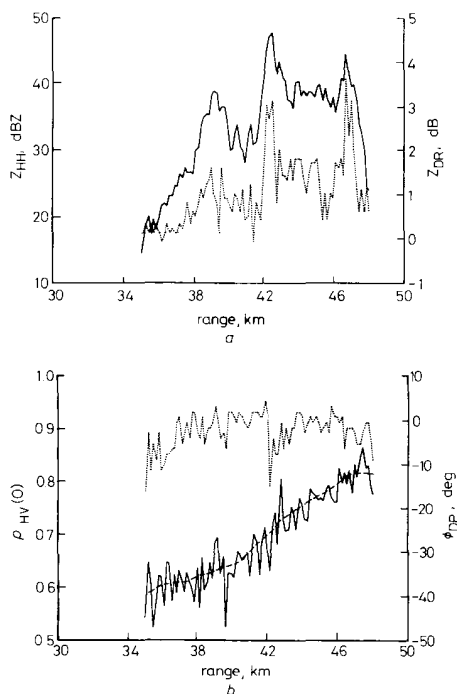


Fig. 11 Range profiles of Poldirad measurements through a convective rainshaft at low elevation angle of 2.1°
23rd August 1988; 16:23; azimuth = 120; elevation = 2.1
a Z_{HH} and Z_{DR} ; — reflectivity, differential reflectivity
b ϕ_{DP} and $\rho_{HV}(0)$; — propagation differential phase, zero-lag crosscorrelation, - - - IIR filtered ϕ_{DP}

A number of range profiles (acquired over 1 min) similar to Fig. 11 were analysed with IIR filtering applied additionally to Z_{HH} and Z_{DR} . This filter was designed to suppress random measurement errors, yet the range gate-to-range gate variability was retained. Fig. 12 shows a scatterplot of Z_{DR} against Z_{HH} which may be compared to the simulations of Fig. 1b. The two dashed lines in Fig. 12 were obtained from Fig. 1b. They represent the upper and lower bounds in Z_{DR} for a given Z_{HH} . The radar measurements in rainfall are thus seen to fall within the bounds established by the simulations.

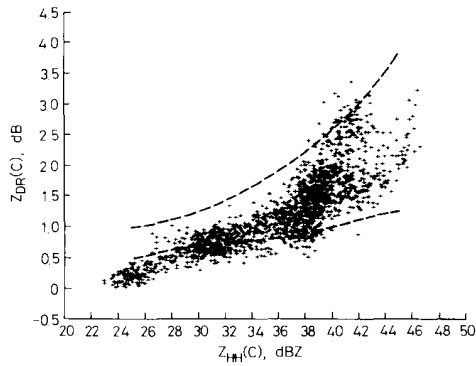


Fig. 12 Scatterplot based on 20 range profiles similar to Fig. 11 of radar measured $Z_{DR}(C)$ against $Z_{HH}(C)$ taken in convective rainfall using Poldirad

Dashed lines are drawn in as the upper and lower bounds from the data of Fig. 1b
23rd August 1988, time = 16 : 23 : 30-16 : 24 : 14

We now consider the ray profile taken through another isolated convective cell on 23rd August, 1988 with higher Z_{HH} values. This case is described in some detail in Reference 23. Fig. 13 shows the ray profile: Fig. 13a shows Z_{HH} and Z_{DR} and Fig. 13b shows ϕ_{DP} and $\rho_{HV}(0)$. Note the very high Z_{DR} in the range 57–58 km, as well as the relatively low $\rho_{HV}(0)$ values. The ϕ_{DP} profile consists of ‘bumps’ superposed on a monotonic increasing trend; these ‘bumps’ are possibly due to differential phase shift on backscatter (δ). The IIR filtered version of ϕ_{DP} is shown by the dashed line in Fig. 13b, the filter being designed to preserve the ‘bumps’ rather than the mean trend with range. Note that the ϕ_{DP} ‘bumps’ centred at ranges 58, 60.5 and 62.75 km are correlated with Z_{DR} peaks of 6, 4 and 3 dB, respectively, and possibly with local minima in $\rho_{HV}(0)$. In the range interval

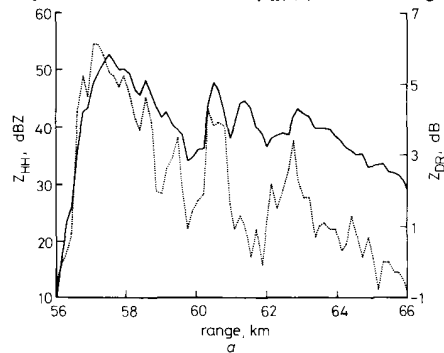


Fig. 13 Range profiles of Poldirad measurements taken through a convective storm

23rd August 1988; 15 : 20; azimuth = 115; elevation = 1.65
a Z_{HH} and Z_{DR} : — reflectivity, differential reflectivity
b ϕ_{DP} and $\rho_{HV}(0)$: — propagation differential phase, zero-lag cross-correlation, - - - IIR filtered ϕ_{DP}
The filter is designed to preserve the ‘bumps’ due to backscatter differential phase in the raw ϕ_{DP} range profile

57–58.5 km we can estimate δ to be in the range 13–18°, Z_{DR} in the range 4–6 dB, and reflectivity 45–55 dBZ. The significantly low values of $\rho_{HV}(0)$ imply that rain mixed with ice (possibly small, melting hailstones) is occurring in the range interval 57–58.5 km. The steady decrease in Z_{DR} with range beyond 58 km (except for local peaks at 60.5 and 63 km) is caused by differential attenuation. This ray profile shows the difficulty of separating out backscatter effects due to δ from forward-scatter effects, i.e. estimating K_{DP} , using just the ϕ_{DP} range profile.

Fig. 14a shows Z_{DR} against Z_{HH} obtained from 20 profiles (over a 1 min time interval) similar to Fig. 13

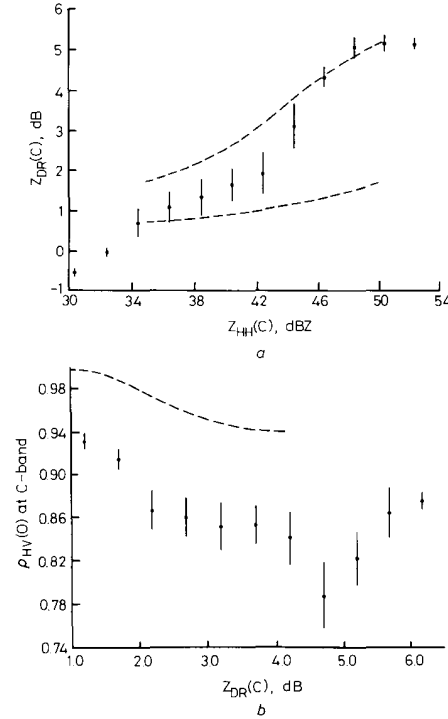


Fig. 14 Averaged radar data based on 20 range profiles similar to Fig. 13 taken in the same convective storm

Vertical lines correspond to the standard deviation
a Z_{DR} data have been averaged over 3 dB categories of Z_{HH}
b $\rho_{HV}(0)$ data have been averaged over 0.2 dB categories of Z_{DR}

(same azimuth and elevation). The Z_{DR} data have been averaged over 3 dB categories of Z_{HH} . Two distinct Z_{DR} regions may be identified, corresponding to $Z_{HH} < 45$ dBZ and $Z_{HH} > 45$ dBZ. For $Z_{HH} < 45$ dBZ the radar data fall within the 'natural' rainfall zone shown in Fig. 1b while for $Z_{HH} > 45$ dBZ, the radar Z_{DR} exceeds the theoretical rain values (at comparable reflectivity levels). Fig. 14b shows $\rho_{HV}(0)$ against Z_{DR} for the 20 ray profiles. The $\rho_{HV}(0)$ data have been averaged over 0.2 dB categories of Z_{DR} . At high Z_{DR} , the $\rho_{HV}(0)$ values are significantly smaller than expected for rainfall, see Fig. 3b. We interpret the high Z_{HH} , high Z_{DR} , nonzero δ and lower $\rho_{HV}(0)$ as being due to rain mixed with small, melting hail.

5 Summary and conclusions

Emphasis in this paper has been on presenting experimental data from three radars: the NCAR S-band CP-2 radar, the NSSL S-band Cimarron radar and the DLR C-band Poldirad radar. These radars can measure differential reflectivity Z_{DR} , the (zero-lag) crosscorrelation coefficient $\rho_{HV}(0)$, and the propagation differential phase (ϕ_{DP}) between H and V polarisation states. The radars were operated in a special time series mode. The transmitted polarisation state was switched between H and V states on a pulse-to-pulse basis. The received signal was always copolar to that transmitted. Data in the form of range profiles of reflectivity, Z_{DR} , $\rho_{HV}(0)$ and ϕ_{DP} were presented in convective storms. Based on the measurements and a raindrop model, inferences were made regarding the precipitation medium, e.g. rain or rain mixed with ice (hail) within the convective precipitation shaft; or oriented ice crystals mixed with aggregates in the stratiform anvil region of convective storms or meso-scale convective complexes. A raindrop model with gamma raindrop size distributions was used to simulate the radar parameters at S- and C-bands. The three gamma parameters (N_o , D_o , m) were varied over a wide range encompassing a variety of rainfall types. Radar measurements in rainfall were found to be in good, general agreement with the simulations. We also show that ϕ_{DP} at C-band need not be monotonic increasing with range, rather the range profile is monotonic increasing with 'bumps' superimposed due to regions of nonzero δ , e.g. regions of large raindrops or small, partially melted ice.

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