Detection and Estimation of Reflectivity Gradients in the Radar Resolution Volume Using Multiparameter Radar Measurements

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***Abstract*— Multiparameter radar measurements of rainfall, namely, reflectivity factor Z_H, differential reflectivity Z_{DR}, and specific differential phase K_{DP} lie in a constrained three-dimensional (3-D) space and therefore measurement of Z_H, Z_{DR}, or K_{DP} should be consistent with the other two. This self-consistency relationship between Z_H, Z_{DR}, and K_{DP} is valid when the radar resolution volume is homogeneous. When there are reflectivity gradients within the radar resolution cell, the self-consistency relation is perturbed. This perturbation can be utilized to detect the presence of gradients in the radar resolution volume. This paper presents a technique to detect and estimate reflectivity gradients in the resolution cell. The technique is evaluated using theoretical analysis as well as experimental data collected by the NCAR CP-2 radar. It is demonstrated that the presence of reflectivity gradients larger than a few decibels can be detected using the algorithm developed in this paper.**

***Index Terms*— Multiparameter, polarimetry, precipitation, radar resolution.**

I. Introduction

THE CHARACTERISTICS of polarization diversity measurements in rain are determined by the shape and size distribution of raindrops. The shape of a raindrop is determined by the forces due to the surface tension, and hydrostatic and aerodynamic pressures due to airflow around the raindrop. Medium and large size raindrops (>2 mm in diameter) are nonspherical. The shape of raindrops changes with the size and can be approximately described by an oblate spheroid with the symmetry axis in the vertical direction [1], [2]. The properties of the size-shape relationship of raindrops translate directly into features of polarization diversity measurements in rainfall. Theoretical calculation and radar observations suggest that polarization diversity measurements of rain, namely, radar reflectivity factor (Z_H), differential reflectivity (Z_{DR}), and specific differential phase (K_{DP}) lie in a limited three-dimensional (3-D) space [3] and therefore measurement of (Z_H), (Z_{DR}), or (K_{DP}) should be consistent with the other two. This self-consistency feature has been used in many practical applications. Aydin *et al.* [4] have used the deviation from the self-consistency region of (Z_H, Z_{DR}) space to derive a hail detection signal (H_{DR}). Rain region in (Z_H, K_{DP}) space is used by Balakrishnan and Zrnic [5] to discriminate between rain and hail. Gorgucci *et al.* [6] have utilized the self-consistency principle to evaluate absolute calibration errors. In this paper, we present the utilization of self-consistency to detect and estimate large reflectivity gradients in the radar resolution volume. Nonuniform resolution volume caused by antenna motion results in reflectivity gradient within the resolution volume. This gradient can be easily recognized by the bias measurement, which is the difference between the reflectivity estimates from log and linear receivers (Scarchilli *et al.* [7]). However, if the antenna is not moving fast or is stationary, the resolution volume can still be inhomogeneous, as is commonly observed with large resolution volume. Such inhomogeneity cannot be detected using bias measurement. This paper describes a technique to detect and estimate inhomogeneity of the radar resolution volume independent of the antenna motion. Radar parameter estimates from inhomogeneous radar resolution volume are usually biased, especially when nonlinear algorithms are involved in the estimation process, such as $Z-R$ (rainfall) relation and velocity estimate. In the presence of strong reflectivity gradient, the relationship between measured reflectivity and rainfall will change for an assumed $Z-R$ equation in the absence of gradients. This can manifest itself as range-dependent $Z-R$ relation because there is a greater chance for the radar resolution volume to be inhomogeneous due to larger volume as the range increases. Therefore, it is important to know the presence of gradients within the radar resolution volume. In addition, it is also important to know how large is the gradient in the resolution volume. This paper attempts to address this issue using multiparameter radar measurements.

Our paper is organized as follows. Section II describes the measurement of K_{DP} from a nonuniform measurement cell, and utilizing the self-consistency requirement, an algorithm to measure reflectivity gradients in the radar resolution volume is obtained. Section III analyzes the algorithm for different reflectivity models within the resolution volume. The accuracy of detection and measurements of reflectivity gradients in the radar resolution cell is given in Section IV. Section V presents application of the techniques developed in this paper to the data collected by NCAR CP-2 radar over convective storms. Section VI summarizes the important results of this paper.

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II. Measurement of K_{DP} from Inhomogeneous Radar Volume

An ensemble of hydrometeors within a radar resolution volume produces a net voltage R_H and R_V, received at horizontal and vertical polarization, that can be obtained as is a superposition of voltage from each scatterer. The mean value of R_H and R_V is zero; the mean intensity and covariance can be obtained from second-order moments as [8]

$$\langle R_H R_H^* \rangle = \left\langle \sum_{i=1}^{n} (f_H)_i (f_H)_i^* (s_{HH})_i (s_{HH})_i^* \right\rangle \tag{1a}$$

$$\langle R_H R_V^* \rangle = \left\langle \sum_{i=1}^{n} (f_H)_i (f_V)_i^* (s_{HH})_i (s_{VV})_i^* e^{j(K_H - K_V) r_i} \right\rangle \tag{1b}$$

where the angle brackets $\langle\,\rangle$ indicate expectation and * indicates complex conjugation, n is the number of the scatterers, $(s_{HH})_i$ and $(s_{VV})_i$ are the diagonal elements of the backscatter matrix for individual particles, $(f_{H,V})_i$ contain the radar constant, range weighting function, and antenna pattern function for the two polarizations, r_i is the range of the ith scatterer, and K_H, K_V is the specific propagation phase at horizontal and vertical polarization.

If the radar resolution volume is composed of m distinct regions that are homogeneous in range, we can simplify the relation given by (1b) as

$$\langle R_H R_V^* \rangle = \sum_{l=1}^{m} \left[\int_{V_l} (f_H)_l (f_V)_l^* dV_l \right] \cdot \langle (s_{HH})_l (s_{VV})_l^* \rangle e^{-j(K_H - K_V)_l r}. \tag{2}$$

Equation (2) can be rearranged as

$$\langle R_H R_V^* \rangle = \sum_{l=1}^{m} (A_H)_l (A_V)_l^* e^{-j(K_H - K_V)_l r} \tag{3}$$

where $(A_H)_l$ and $(A_H)_l$ are the complex horizontal and vertical amplitudes of the signal received from the elemental volume V_l; they are related to the backscattering matrix terms by

$$(A_H A_V^*)_l = \left[\int_{V_l} (f_H)_l (f_V^*)_l \, dV_l \right] \langle (s_{HH} s_{VV}^*)_l \rangle. \tag{4}$$

The phase term in (2) is due to a combination of the following:

1) propagation effects;
2) backscatter differential phase;
3) different phase of antenna pattern at horizontal and vertical polarization, which can be defined radar system differential phase.

At S-band, the differential backscatter phase shift between vertically and horizontally polarized waves is very small (0.2° for the biggest drops); moreover, for simplicity and without loss of generality, it can be assumed that the radar system differential phase is zero. Thus, (3) becomes

$$\langle R_H R_V^* \rangle = \sum_{l=1}^{m} |(A_H)_l||(A_V)_l| e^{-j(K_{DP})_l r} \tag{5}$$

where $|\,|$ indicates absolute value and $K_{DP} = K_H - K_V$ is the specific differential phase shift due to propagation. The absolute values of the complex amplitudes A_H and A_V can be related to the power by the following relationship:

$$|A_H||A_V| = P_H 10^{-0.05 Z_{DR}} \tag{6}$$

where Z_{DR} is the differential reflectivity in decibels. The argument of the complex quantity (5) is given by

$$\mathrm{Arg}\,\langle R_H R_V^* \rangle = \mathrm{Arg}\left[\sum_{l=1}^{m} |(A_H)_l||(A_V)_l| e^{-j(K_{DP})_l r} \right]. \tag{7}$$

Equation (7) gives the expected value of the cumulative differential phase shift Φ_{DP} over the beam at the range r; this is obtained as a linear combination of the cumulative differential phase shift in each uniform region, weighted by the absolute values of the complex amplitudes of received signals at vertical and horizontal polarization. Assuming that Φ_{DP} varies linearly within a small range bin Δr, then the expected value of specific differential phase shift can be easily obtained from (7) as

$$\langle K_{DP} \rangle = \frac{1}{\Delta r} \mathrm{Arg}\left[\sum_{l=1}^{m} |(A_H)_l||(A_V)_l| e^{-j(K_{DP})_l r} \right]. \tag{8}$$

Theoretical calculation and radar observations [3] suggest that the polarimetric measurements of reflectivity factor at horizontal polarization (Z_H), differential reflectivity (Z_{DR}), and specific differential phase (K_{DP}) lie in a limited 3-D space for rain medium. In other words, there is a self-consistency requirement in polarization diversity radar measurements of rainfall. This constraint enables parameterization of K_{DP} in terms of Z_H and Z_{DR} as

$$K'_{DP} = C Z_H^{\alpha} 10^{-\beta Z_{DR}} \tag{9}$$

where K'_{DP} is the parameterized estimate of K_{DP}, Z_H is in units mm^6 m^{-3}, and Z_{DR} is in decibels. It should be noted here that K'_{DP} indicates an estimate based on Z_H and Z_{DR} and not from a profile of differential phase measurements. The coefficients C, α, and β change as a function of the frequency. The values of C, α, and β at S- and C-bands are given as follows:

S-band (10 cm)

$$C = 1.05 \times 10^{-4}, \quad \alpha = 0.96, \quad \beta = 0.26 \tag{10a}$$

C-band (5.5 cm)

$$C = 1.46 \times 10^{-4}, \quad \alpha = 0.98, \quad \beta = 0.20. \tag{10b}$$

Scarchilli *et al.* [3] have shown that (9) can approximate K_{DP} fairly well in absence of measurement errors. Gorgucci *et al.* [6] have utilized this feature to calibrate weather radars; in this section, we show that the self-consistency principle could give quantitative information about reflectivity gradient within the resolution volume.

For the nonuniform resolution volume, the estimate K'_{DP} can be written as

$$K'_{DP} = C\left[\frac{1}{m}\sum_{l=1}^{m}(Z_H)_l\right]^{\alpha} \cdot 10^{-\beta 10 \log\left\{\sum_{l=1}^{m}(Z_H)_l / \sum_{l=1}^{m}(Z_V)_l\right\}}. \quad (11)$$

If the radar resolution volume is uniform, the average Z_H and Z_{DR} will correspond to the average K_{DP} given by (8). However, in the presence of gradients, this will not be valid. Therefore, we can evaluate a coefficient ν that will give a measure of the nonuniform resolution volume. We define the ratio between the directly measured K_{DP} to parameterized K'_{DP} as ν given by

$$\nu = \frac{K_{DP}}{K'_{DP}}. \quad (12)$$

From (8) and (11), it can be easily pointed out that, for uniform reflectivity field, the expected value of ν is nearly one.

III. Analysis of Models for Inhomogeneous Radar Resolution Volume

In this section, we study the sensitivity of ν with gradients in the radar resolution volume for two cases, namely, 1) the case corresponding to beam blocking and 2) the case in which the reflectivity varies linearly on decibel scale.

A. Beam Blocking

Low elevation radar scans suffer beam blockage from elevated ground target or mountains. When the beam is partially blocked, the echo received from the ranges farther than the blocking target will be reduced by the fraction f of the beam volume filled with rain. It can be easily seen that both radar reflectivity at horizontal Z_H and at vertical polarization Z_V are reduced in proportion to the amount of beam blockage; thus, the measurement of Z_{DR} over the beam is independent of the beam blockage. Under those considerations, the estimate (11) becomes

$$K'_{DP} = C(fZ_H)^{\alpha} 10^{-\beta Z_{DR}}. \quad (13)$$

On the other hand, the expected value of K_{DP} can be expressed as

$$\langle K_{DP}\rangle = \frac{1}{\Delta r}\,\mathrm{Arg}\,(Z_H 10^{-0.05 Z_{DR}} e^{-jK_{DP}\Delta r}) = K_{DP}. \quad (14)$$

This result shows that, similar to Z_{DR} measurement, K_{DP} is also independent of the beam filling. Finally the ratio ν between K_{DP} and K'_{DP} gives

$$\langle \nu \rangle = 1/f^{\alpha}. \quad (15)$$

From (15) we obtain a quantitative estimate of the power reduction as a function of the amount of the beam blocking, as it is expected.

B. Constant Reflectivity Gradient

Cloud model and measurements of raindrop size distribution (RSD) at the surface show that a gamma distribution model describes natural variations in the RSD [9]

$$N(D) = N_0 D^{\mu} e^{-(3.67+\mu)\,D/D_o} \quad (\mathrm{m}^{-3}\,\mathrm{mm}^{-1}) \quad (16)$$

where $N(D)$ is the number of raindrops per unit volume per unit size interval D to $D + \Delta D$ and N_o, D_o, and μ are parameters of the gamma distribution.

The radar parameters of the rain medium, namely, $(Z_{H,V}, Z_{DR}, K_{DP})$, can be expressed in terms of the RSD as follows:

$$Z_{H,V} = \frac{\lambda^4}{\pi^5 |K|^2}\int \sigma_{H,V}(D)N(D)dD \quad (\mathrm{mm}^6\,\mathrm{m}^{-3}) \quad (17)$$

where $Z_{H,V}$ and $\sigma_{H,V}$ represent the reflectivity factors and radar cross sections at horizontal and vertical polarization, respectively, λ is the wavelength, and $K = (\epsilon_r - 1)/(\epsilon_r + 2)$, where ϵ_r is the dielectric constant of water

$$Z_{DR} = \frac{\int \sigma_H(D)N(D)dD}{\int \sigma_V(D)N(D)dD} \quad (18)$$

$$K_{DP} = \frac{180\lambda}{\pi}\,\mathrm{Re}\int [F_H(D) - F_V(D)]N(D)dD \quad (\deg/\mathrm{km}) \quad (19)$$

where F_H and F_V are the forward scatter amplitudes at H and V polarization, respectively. It has been often observed that radar reflectivity factor Z_H expressed in dBZ varies linearly in space within distances comparable to the beamwidth [10]. Let us assume that the variation of Z_H occurs over cross range, that is, along the elevation/azimuth axis. One simple way to obtain this variation is by exponential variation of the parameter N_o as

$$N_o = (N_o)_c \exp(0.23 G_{No} x) \quad (20)$$

where $(N_o)_c$ represents the value of N_o at the center of the beam and G_{No} is the variation of N_o expressed in decibels/kilometer. Assuming that D_o and μ are constant, it is easy to derive from (17) and (18) that Z_{DR} remains constant

$$Z_{DR} = \mathrm{const} \quad (21)$$

whereas Z_H varies as

$$Z_H = (Z_H)_c \exp(0.23 G_{No} x) \quad (22)$$

where $(Z_H)_c$ is the value of Z_H at the center of the beam. With those assumptions, the estimate K'_{DP} can be written

$$K'_{DP} = C(Z_H)_c^{\alpha} 10^{-\beta Z_{DR}}\left[\frac{1}{L}\int_{-L/2}^{L/2}\exp(0.23 G_{No} x)\,dx\right]^{\alpha} \quad (23)$$

where L is the beam length in elevation/azimuth direction. Evaluating the integral in (23), we obtain

$$K'_{DP} = (K'_{DP})_c\left(\frac{e^{0.23 G_{No} L/2} - e^{-0.23 G_{No} L/2}}{0.23 G_{No} L}\right)^{\alpha} \quad (24)$$

where $(K'_{DP})_c$ is the value of K'_{DP} at the center of the beam. We can observe that (24) is a monotonic increasing function with the reflectivity gradient. For uniform reflectivity, $G_{No} = 0$ and $K'_{DP} = (K'_{DP})_c$, as expected. On the other hand, taking account of (21) and (22) and substituting the summation with integral, the expected value of K_{DP} can be written

$$\langle K_{DP} \rangle = \frac{1}{\Delta r} \operatorname{Arg}\left\{ \int_{-L/2}^{L/2} e^{0.23 G_{No} x} \cdot \exp\left[j \Delta r (K_{DP})_c e^{0.23 G_{No} x} \right] dx \right\} \quad (25)$$

which simplifies to

$$\langle K_{DP} \rangle = (K_{DP})_c \frac{e^{0.23 G_{No} L/2} + e^{-0.23 G_{No} L/2}}{2} \quad (26)$$

where $(K_{DP})_c$ is the value of K_{DP} at the center of the beam. Using the parameterization (9) at the center of the beam, we can assume that $(K_{DP})_c = (K'_{DP})_c$. Finally, combining (24) and (26) gives

$$\langle \nu \rangle = \frac{e^z + e^{-z}}{2} \left[\frac{z}{(e^z - e^{-z})} \right]^{\alpha} \quad (27)$$

where $z = 0.23 G_{No} L/2$. It can be pointed out that, for uniform reflectivity, that is, for $z = 0$, the parameter $\nu = 1$ as it is expected. Fig. 1 shows the plot of the ratio ν versus the variation $G_H = G_{No} L$ of the reflectivity along the path. It is easy to see that the ratio ν is independent of the sign of gradient and not very sensitive to reflectivity variation up to 5 dB. Moreover, when G_H is larger than 10 dB, then ν increases nearly linearly with the variation of reflectivity along the path. From (27), it can be observed that the reflectivity gradient over the beam can be estimated from the measurements of K'_{DP} and K_{DP}. In the following section, the accuracy of gradient estimation is evaluated.

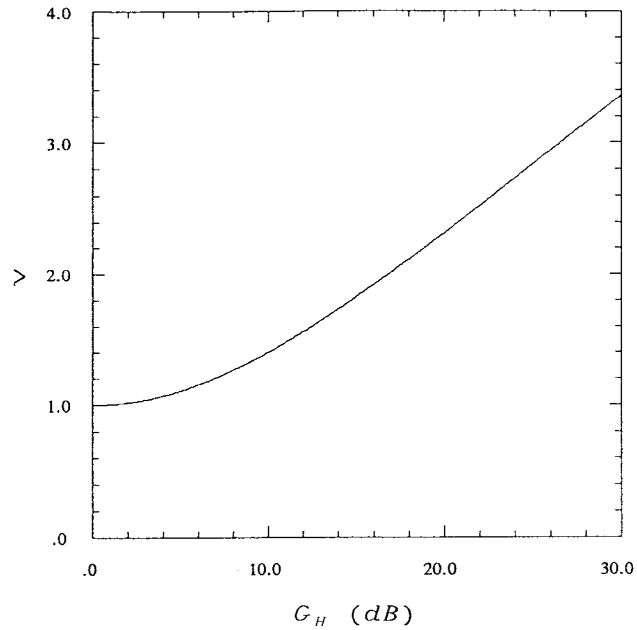

Fig. 1. Ratio ν between specific differential phase shift K_{DP} and the parameterized K'_{DP} as a function of the reflectivity variation G_H, expressed in decibels.

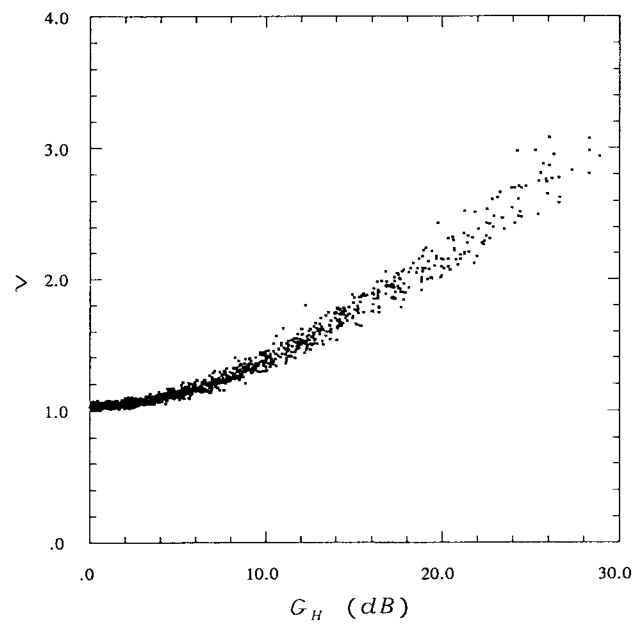

Fig. 2. Scatterplot of the ratio ν between specific differential phase shift K_{DP} and the parameterized K'_{DP} as a function of the reflectivity variation G_H, expressed in decibels, in absence of measurement error.

IV. Simulation Analysis

In this section, we simulate radars returns to study the error in the measurement of the coefficient ν. The radar measurements Z_H, Z_{DR}, and Φ_{DP} along the path and over the nonuniform resolution volume are constructed as follows:

1) total length in elevation/azimuth 3 km;
2) subvolume length in elevation/azimuth 150 m;
3) variation of reflectivity in elevation/azimuth between 0 and 30 dB;
4) reflectivity value at the starting elevation point between 25 and 55 dBZ;
5) maximum reflectivity along the path less than 55 dBZ.

The reflectivity profile is assumed linear on decibel scale. Once the reflectivity is fixed at an elemental resolution volume, the parameters of the RSD, namely, N_0, D_0, and μ, are chosen randomly within the limits suggested by Ulbrich [9] and under the constraint that the RSD yields the current reflectivity value in the elemental resolution volume. Subsequently, the values of Z_{DR} and K_{DP} are computed for the elevation location. This procedure yields a wide variety of profiles of Z_H, Z_{DR}, and K_{DP} so that the technique to retrieve reflectivity gradient can be tested under all conditions. Utilizing (8) and (11), the estimates K_{DP} and K'_{DP} over the beam can be obtained.

Fig. 2 shows the scatter plot of the ratio ν between the estimates K_{DP} and K'_{DP} versus the variation of the reflectivity G_H along the path. At first glance, it can be noted that the theoretical curve of Fig. 1 fits fairly well the scatterplot of Fig. 2. The variation of reflectivity G_H can be estimated from the ratio ν using nonlinear regression analysis. Fig. 3 shows

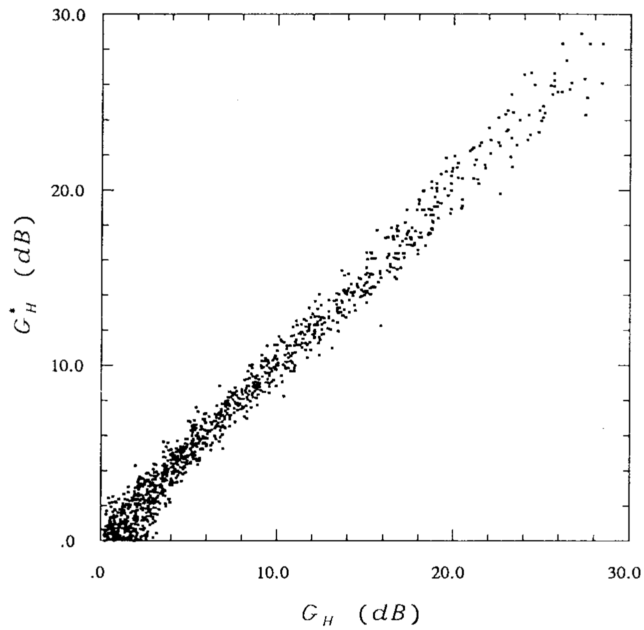

Fig. 3. Scatterplot of the retrieved reflectivity variation G^*_H as a function of the true reflectivity variation G_H, expressed in decibels, in absence of measurement error.

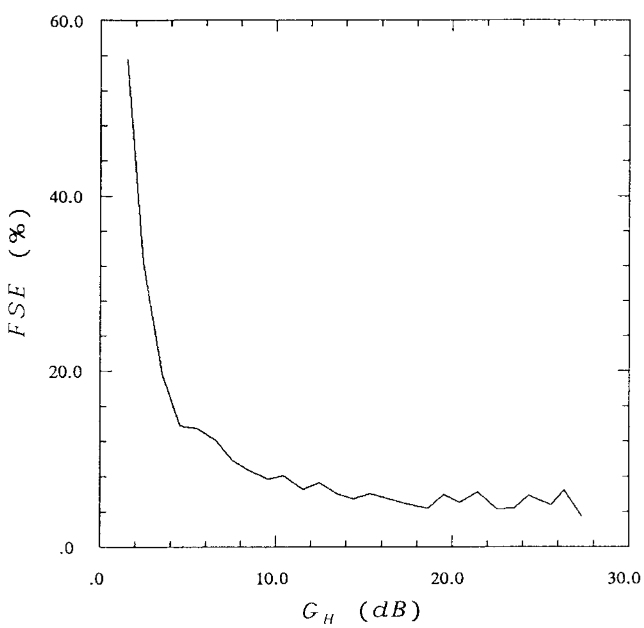

Fig. 4. Fractional standard error (FSE) as a function of true reflectivity variation G_H, expressed in decibels, in absence of measurement error.

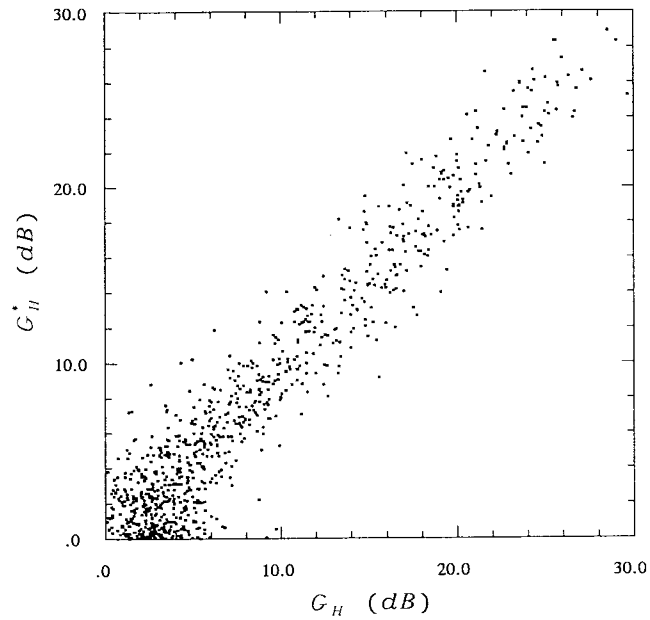

Fig. 5. Scatterplot of the retrieved reflectivity variation G^*_H as a function of the true reflectivity variation G_H, expressed in decibels, in presence of measurement error.

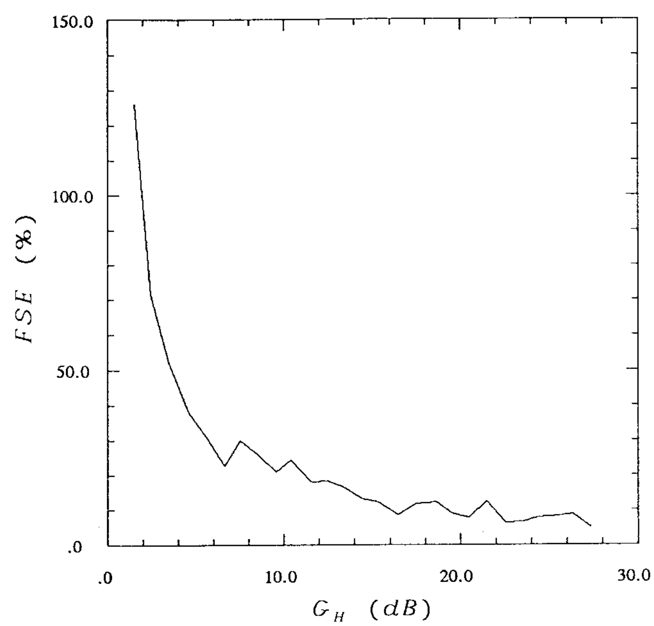

Fig. 6. Fractional standard error (FSE) as a function of true reflectivity variation G_H, expressed in decibels, in presence of measurement error.

the scatter between the true variation of reflectivity G_H and the estimate G^*_H obtained from the measurements of the ratio ν. The accuracy of the estimation process can be observed from Fig. 4, which shows the fractional standard error (FSE) as a function of the true variation. We can note that FSE is greater than 50% for the reflectivity variation less than 2 dB; it decreases quickly to 6% for $G_H = 10$ dB and remains fairly constant for $G_H > 10$ dB.

It should be noted here that the scatter diagram of Fig. 3 is obtained in the absence of measurement error. The radar estimates with signal fluctuations are simulated using the procedure given by Chandrasekar *et al.* [11]. The parameters assumed in the simulation of the measurement error are as follows:

1) radar frequency 3 GHz;
2) pulse repetition time 1 ms;
3) number of sample pairs 64;
4) Doppler spectrum width 2 m/s.

Fig. 5 shows the scatter of the variation G_H versus the estimate G^*_H, and Fig. 6 shows the accuracy of the retrieval process in the presence of measurement error. We can see that the signal fluctuations affect the estimates of reflectivity gradients significantly for $G_H < 5$ dB, and for $G_H > 10$ dB, the fractional standard error varies between 10 and 20%.

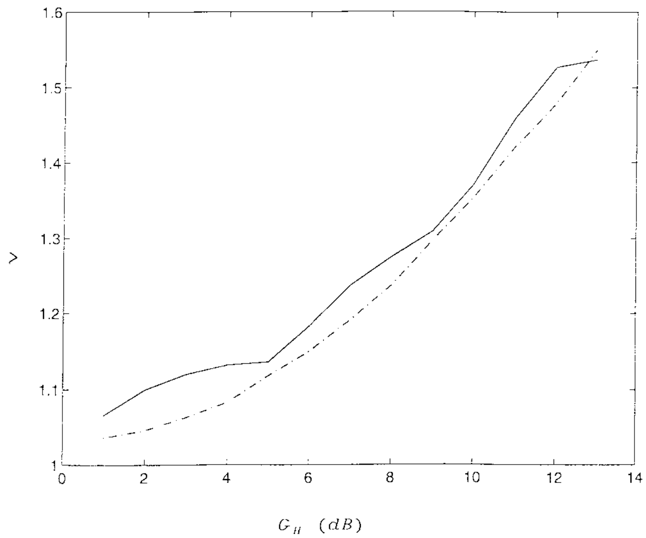

Fig. 7. Mean ratio ν versus the reflectivity variation G_H, expressed in decibels, from radar data collected by NCAR CP-2 (solid line) and from simulation data (dash-dotted line).

V. Data Analysis

Data collected during the Cape experiments is utilized to verify the algorithm developed in this paper. Toward the end of the Cape experiments, the NCAR CP-2 radar was equipped with an auxiliary signal processor developed at Colorado State University to obtain differential phase measurements Φ_{DP} in addition to Z_H and Z_{DR}. The data were collected on September 29, 1991, and came from different kinds of antenna scans (RHI, PPI, surveillance mode). The measurements were obtained integrating on 64 sample pairs, with a typical scan rate of 8° s^{-1}. In order to avoid contamination from ground clutter, the minimum elevation was chosen equal to 1.5°, while potential contamination from hail/ice regions was reduced thresholds on the altitude values of 3 km. The radar data were divided into 4.5-km paths corresponding to 15 gates with gate spacing of 300 m; for our analysis, we have considered only the "quasiuniform" paths where the reflectivity value in each range gate is greater than 35 dBZ and the mean square root reflectivity variation is less than 2 dB. For the resulting "quasiuniform paths," the mean values of Z_H and Z_{DR} are computed and the estimates of K_{DP} are obtained as the slope of the range profile of Φ_{DP}. Finally, the reflectivity fields in azimuth or in elevation are constructed by combining the total number of paths in groups of ten. Fig. 7 shows the mean ratio ν between the estimates $\hat{K}_{DP}$ and $\hat{K}'_{DP}$ obtained from the algorithms (8) and (11), as a function of the excursion of reflectivity expressed in decibels. It can be seen that the experimental results agree reasonably well with theoretical results and demonstrate the potential of the technique described here to detect and estimate reflectivity gradient greater than a few decibels.

VI. Summary and Conclusion

The properties of shape and size distribution of raindrops translate into characteristics of polarization diversity measurements. Theoretical calculation and radar observations suggest that polarization diversity measurements in rain, namely, reflectivity factor, differential reflectivity, and specific differential phase shift lie in a constrained 3-D space. This self-consistency feature of polarization diversity measurement is used to parameterize K_{DP} as a function of reflectivity and differential reflectivity. Subsequently, the ratio between this parameterized K'_{DP} and the directly measured K_{DP} is computed to detect and estimate reflectivity gradient within the radar resolution volume. Multiparameter radar measurements over a large number of precipitation paths were simulated to evaluate the capability of the procedure developed in this paper to estimate the reflectivity gradient. Theoretical analysis as well as simulation study were used to demonstrate the sensitivity of the ratio between measured K_{DP} and K'_{DP} to the reflectivity gradients. It was shown that, in the presence of measurement error, the accuracy of the retrieval process is reliable for reflectivity variation G_H greater than 5–7 dB. Multiparameter data collected by the NCAR CP-2 radar during the Cape experiment were utilized to verify the procedure for gradient estimation developed in this paper. The experimental results demonstrate the potential to estimate reflectivity excursion greater than 5 dB using the technique described in this paper.

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G. Scarchilli, for a photograph and biography, see p. 276 of the January 1999 issue of this Transactions.

E. Gorgucci, for a photograph and biography, see p. 276 of the January 1999 issue of this Transactions.

V. Chandrasekar (S'83–M'83), photograph and biography not available at the time of publication.