

Rain-Rate Estimation in the Presence of Hail Using S-Band Specific Differential Phase and Other Radar Parameters

K. AYDIN

Department of Electrical Engineering, The Pennsylvania State University, University Park, Pennsylvania

V. N. BRINGI AND L. LIU

Department of Electrical Engineering, Colorado State University, Fort Collins, Colorado

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ABSTRACT

Multiparameter radar measurements were made during a heavy rainfall event accompanied by hail in Colorado. Rainfall rates R and accumulation Σ for this event were estimated using S-band specific differential phase K_{DP} , reflectivity factor Z_H , and X-band specific attenuation A_{H3} . These estimates were compared with measurements from a ground-based rain gauge. Both R - K_{DP} and R - A_{H3} relations were in good agreement with the rain gauge data, that is, less than 10% difference in the rainfall accumulations. The R - Z relation produced similar results only when Z_H was truncated at 55 dBZ. This study demonstrates the potential of K_{DP} for estimating rainfall rates in severe storms that may have rain-hail mixtures.

1. Introduction

An important problem in radar meteorology is the estimation of rainfall rate R in heavy precipitation that can lead to flash floods. When such precipitation is composed of a mixture of rain and hail, R - Z_H and R - (Z_H, Z_{DR}) relations (Battan 1973; Seliga and Bringi 1976) can lead to significant errors. In the case of R - Z_H , since Z_H is proportional to the sixth moment of particle size in the Rayleigh regime, it is significantly affected by hailstones that are larger in size than most raindrops. On the other hand, the R - (Z_H, Z_{DR}) relation is affected by this bias in Z_H as well as bias in Z_{DR} toward the larger hailstones. Since Z_{DR} is the reflectivity-weighted mean axial ratio (Jameson 1983) and hailstones have mean axial ratios much closer to 1 (as compared to large raindrops), its value is significantly reduced by the presence of hailstones. In fact these aspects of Z_H and Z_{DR} are used for detecting hail (Bringi et al. 1984; Aydin et al. 1986).

This paper presents a case study of S-band (10.9-cm wavelength) radar rainfall estimation in the presence of hail using one-way specific differential phase K_{DP} between H and V polarizations compared with a ground-based rain gauge. One-way specific attenuation A_{H3} at X band (3.2-cm wavelength) is used as another

estimator of R for comparison with the rain gauge in the same rainfall event. Both K_{DP} and A_{H3} are forward-scattering parameters as opposed to Z_H and Z_{DR} , which are backscattering parameters. The specific differential phase K_{DP} is not affected very much by the presence of hailstones that have mean axial ratios close to 1 and/or are tumbling (Balakrishnan and Zrnić 1990). It is dominated by oriented oblate spheroidal raindrops. Therefore, it is a valuable parameter for estimating R in a rain-hail mixture. On the other hand, A_{H3} is proportional to about the third moment of particle size for sizes in the range 3.9–6 mm (Jameson 1991) and therefore is not as significantly affected by hailstones mixed with raindrops as Z_H is at S band. The main drawback of A_{H3} is that two radars are needed to measure it.

2. Rainfall rate-radar parameter relations

Specific differential phase has been considered for estimating rainfall rate (Seliga and Bringi 1978; Doviak and Zrnić 1993) and various estimators have been proposed (Jameson and Mueller 1985; Sachidananda and Zrnić 1986). Several S-band R - K_{DP} relations exist in the literature. Among these are $R = 37.1K_{DP}^{0.866}$ (Sachidananda and Zrnić 1987), and $R = 36.15K_{DP}^{0.84}$ for $0.01^\circ < K_{DP} < 1.5^\circ \text{ km}^{-1}$ and $33.77K_{DP}^{0.97}$, for $1.5^\circ \leq K_{DP} < 7^\circ \text{ km}^{-1}$ (Aydin and Giridhar 1992), which are termed the SZ and AG relationships, respectively. Here we use the relationship (Chandrasekar et al. 1990)

$$R_{KDP} = 40.5K_{DP}^{0.85} \quad (\text{mm h}^{-1}), \quad (1)$$

Corresponding author address: Prof. Kultegin Aydin, Department of Electrical Engineering, The Pennsylvania State University, University Park, PA 16802.

where K_{DP} has units of degrees per kilometer. The parameters a and b of the relation $R_{KDP} = aK_{DP}^b$ are obtained by a nonlinear regression technique. The AG relationship is based on disdrometer measurements of raindrop size distributions. Equation (1) is derived from a gamma drop size distribution by varying the gamma parameters (N_0 , m , D_0) over a wide range (Ulbrich 1983). The SZ relation is based on the Marshall–Palmer (1948) drop size distribution with $N_0 = 8000 \text{ m}^{-3} \text{ mm}^{-1}$. Because (1) incorporates a more general gamma distribution it is used in this paper. The differences between (1) and the SZ and AG relations are less than 6% for $100 \leq R < 200 \text{ mm h}^{-1}$ and less than 12% for $R < 100 \text{ mm h}^{-1}$. Note that (1) produces larger rain rates than both the SZ and AG relations when $R < 147 \text{ mm h}^{-1}$.

The use of specific attenuation at X band (A_{H3}) on a microwave link for estimating rainfall has also been considered (Atlas and Ulbrich 1977). In this study the temperature-averaged relation given by Jameson (1992) is used:

$$R_{AH3} = 54.6 A_{H3}^{0.845} \quad (\text{mm h}^{-1}), \quad (2)$$

where A_{H3} is in decibels per kilometer.

The next section describes how K_{DP} and A_{H3} are estimated. Both estimators are insensitive to the absolute gain of the radars (Doviak and Zrnić 1993).

A Z – R relation adopted for WSR-88D (NEXRAD—Next Generation Weather Radar) operations will also be used to compare its performance. This relation is (Kelsh 1989)

$$R_Z = 0.017 Z^{0.714} \quad (\text{mm h}^{-1}), \quad (3)$$

where Z is in its standard units ($\text{mm}^6 \text{ m}^{-3}$). This Z – R relation is truncated at an operator-specified maximum reflectivity value, depending on the geographical region for which it is used.

3. Heavy rainfall event

On 24 June 1992 a severe storm left nearly 75 mm (3") of rain between 1515 and 1615 MDT in Fort Collins, Colorado. Observers at the main campus of Colorado State University (CSU) noted that precipitation started with a few big drops followed by intense rain and then mixed with hailstones of 15–20 mm in diameter. The storm system moved in the east-southeast direction and was scanned by the CSU-CHILL and NCAR's CP-2 and Mile High radars. An overview of this storm was previously given by Bringi et al. (1993).

Figure 1 is a constant-altitude (1.5 km AGL) PPI (plan position indicator) section from the CSU-CHILL radar at 1536 MDT, showing reflectivity factor Z_H , with Z_{DR} and K_{DP} fields. The peak reflectivity is 63.2 dBZ at $x = -37 \text{ km}$, $y = 16 \text{ km}$, the radar location being at (0, 0). The Z_{DR} hail signature indicates a hail

core at about (−39, 16) km, where $Z_{DR} < 0.5 \text{ dB}$ and $Z_H > 60 \text{ dBZ}$. In fact the entire region with $Z_H > 45 \text{ dBZ}$ and $Z_{DR} < 0.5 \text{ dB}$ likely contains hail (Aydin et al. 1986). The rain gauge is located at (−37.7, 15.3) km, that is, 292.2° azimuth and 40.7-km radial distance from CHILL, and is at the border of the region containing hail.

Figure 1 also shows several regions of high K_{DP} within the $Z_H > 50 \text{ dBZ}$ contour, one of which is in the hail region described above, the peak K_{DP} being $3.6^\circ \text{ km}^{-1}$ at (−38, 16) km. The high values of K_{DP} suggest that rainfall is dominant in this region even though it may contain hail.

Figure 2 shows S-band CSU-CHILL radar measurements of Z_H , K_{DP} , ϕ_{DP} (two-way propagation differential phase shift), Z_{DR} , and R_{KDP} along a ray. The Z_H , Z_{DR} , and ϕ_{DP} data corresponding to 150-m range gates are passed through an infinite impulse response filter (termed “light” filter in Fig. 2) that attenuates spatial fluctuations less than 300 m by more than 15 dB. This “lightly” filtered ϕ_{DP} is adaptively filtered using a finite impulse response filter (termed “adaptive” filter in Fig. 2) that attenuates spatial fluctuations less than 1.5 km by more than 15 dB (Hubbert et al. 1993). Differential phase K_{DP} is then calculated as one-half the slope of the adaptively filtered ϕ_{DP} , $K_{DP} = [\phi_{DP}(r_2) - \phi_{DP}(r_1)]/[2(r_2 - r_1)]$, where $2(r_2 - r_1) = 300 \text{ m}$. The resulting K_{DP} accuracy is estimated to be within $\pm 0.5^\circ \text{ km}^{-1}$. This error estimate is based on analysis of statistical fluctuations of radar data in light rain at vertical incidence where mean K_{DP} should be zero (Liu et al. 1993). We note that Liu et al. (1993) estimated the accuracy of mean K_{DP} as $\pm 0.25^\circ \text{ km}^{-1}$ in conditions of very high ρ_{hv} (> 0.985) and using 128 sample H – V pairs in the estimate of ϕ_{DP} at any one resolution volume. We have degraded this accuracy here by a factor of 2 to account for lowered ρ_{hv} found in convective storms (Liu et al. 1995), and the reduced number of sample H – V pairs (64) used when these 24 June data were collected. Note the high values of K_{DP} in the two cores at about 21 and 42 km, exceeding 6° km^{-1} in the latter. In the core at 42 km, Z_{DR} is very low and fluctuates about 0 dB, whereas Z_H is very high and exceeds 55 dBZ, indicating the presence of hailstones. The rainfall rate R_{KDP} estimated from K_{DP} is above 190 mm h^{-1} in this core.

Figure 3 shows CP-2 radar measurements of Z_H (S band), Z_{H3} (X band), Z_{DR} (S band), dual-frequency ratio $DFR = Z_H - Z_{H3}$ (dB), and R_{AH3} along a ray. The rain gauge is located at 8.2° azimuth and 71.4-km radial distance from the CP-2 radar. The processing of the reflectivity factors and differential reflectivity are the same as described for the CHILL radar measurements. The processing of DFR is identical to that of ϕ_{DP} . The specific attenuation A_{H3} is calculated as one-half the slope of the adaptively filtered DFR just as K_{DP} is obtained from ϕ_{DP} . The accuracy in A_{H3} is es-

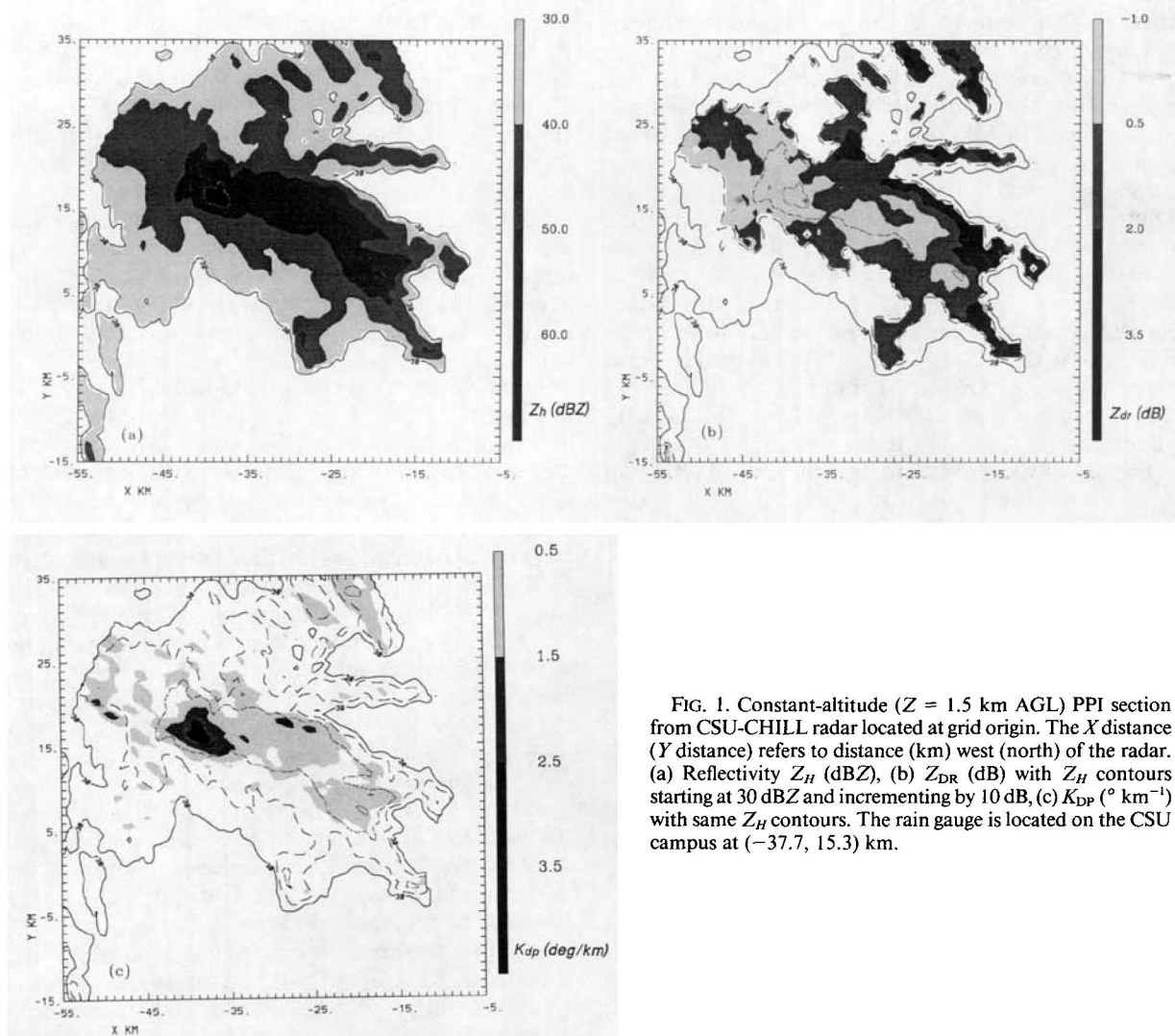


FIG. 1. Constant-altitude ($Z = 1.5$ km AGL) PPI section from CSU-CHILL radar located at grid origin. The X distance (Y distance) refers to distance (km) west (north) of the radar. (a) Reflectivity Z_H (dBZ), (b) Z_{DR} (dB) with Z_H contours starting at 30 dBZ and incrementing by 10 dB, (c) K_{DP} ($^{\circ}$ km $^{-1}$) with same Z_H contours. The rain gauge is located on the CSU campus at $(-37.7, 15.3)$ km.

timated to be ± 0.5 dB km $^{-1}$, which again (has been degraded by a factor of 2) is based on an analysis of statistical fluctuations of DFR data in light rain at vertical incidence where mean A_{H3} should be zero (Liu et al. 1993). Note the intense attenuation at X band as seen in the dramatic reduction of Z_{H3} relative to Z_H as the beam penetrates the core at about 71 km. The rainfall rate R_{AH3} estimated from A_{H3} exceeds 200 mm h $^{-1}$ in this core. Differential reflectivity Z_{DR} in the core is less than 0.5 dB whereas Z_H exceeds 65 dBZ, indicating the presence of hail. The rain gauge is about 2.5 km east of this ray at 71.4-km range. Note that this is the same core seen in Fig. 2 by the CHILL radar at 42 km, but at a slightly earlier time. Also note that beyond 74-km range the X-band signal falls below noise level.

4. Radar-rain gauge comparison of rainfall

The rain gauge used in this study was operated by the Colorado Climate Center and was located at the

Colorado State University main campus weather station. It was a 30.5-cm (12") dual transverse universal weighing-bucket gauge with an analog chart recorder. The rainfall rates estimated from the graphical recording were obtained from 5-min accumulations. It is possible to make $\pm 15\%$ error in R due to errors reading the graph resulting from heavy rainfall and hail. However, the error in reading the total accumulation is very low, less than about 1 mm. These errors are separate from the measurement errors of the rain gauge itself. For example, the rain gauge can experience reduced catch during wind-driven precipitation as was probably the case during the 24 June storm. Based on experience with gauges of this type, the errors due to the wind-driven rain and random sampling are likely to be approximately 15%–20% (N. Doesken 1994, personal communication). In this case the official standard manual rain gauge, from which historic records are derived, indicated 14% less rainfall accumulation compared to the recording

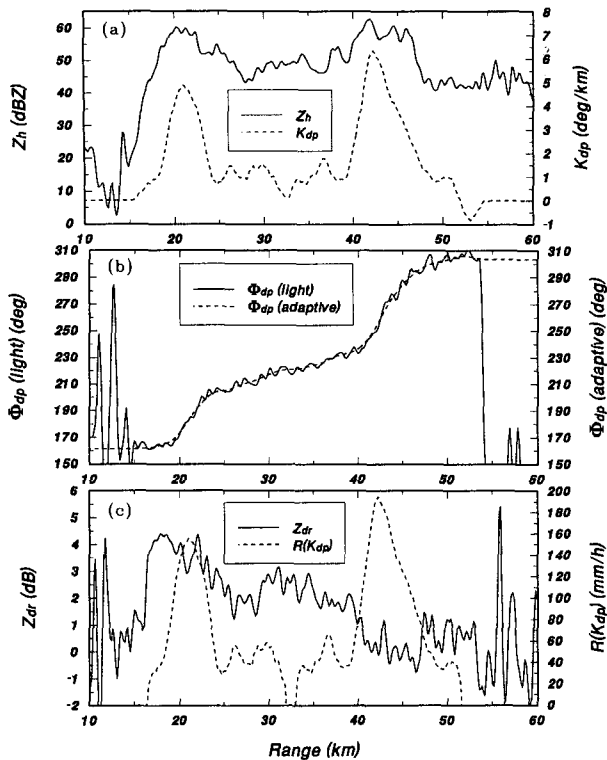


FIG. 2. Range profiles of (a) Z_H and K_{DP} , (b) ϕ_{DP} (both lightly and adaptively filtered versions), and (c) Z_{DR} and $R_{K_{DP}}$, from a CHILL radar ray through the storm system shown in Fig. 1, at time 1538:38 MDT 24 June 1992, and with elevation and azimuth angles being 0.9° and 292.2° , respectively.

weighing-bucket gauge that was located 3 m away (N. Doesken 1994, personal communication).

Two methods were used to compare the radar estimates of R with those measured by the rain gauge. Method 1 involved taking into account the horizontal transport of raindrops due to rain cell motion and integrating R along the cell path. Method 2 considered only the range gate directly above the rain gauge. A detailed description of these methods and the resulting rain gauge comparisons are given below.

a. Method 1

The track of the cell that passed over the rain gauge was determined by observing the location of the K_{DP} core at different times during the rainfall event. This analysis showed that the cell moved in a direction about 70° from the north at a speed of 4 m s^{-1} . It should be noted that the results presented here were negligibly affected when the cell track direction was taken as 60° or 80° from the north. Similarly, small changes ($\pm 0.5 \text{ m s}^{-1}$) in the velocity of the cell had negligible effects on the results. The lowest elevation angle PPI scans (0.8° for CHILL and 0.5° for CP-2, both corresponding

to beam centers 600 m above ground at the rain gauge location) were used to estimate rainfall rate. Eight of the lowest elevation angle scans were available from each radar at approximate intervals of 4 min for CSU-CHILL and 6 min for CP-2. This provided observations of the rain as close as possible to the ground, reducing errors due to advection. Along the cell track a 1200-m section was selected for estimating R . This corresponds to a 5-min travel distance of the cell that matches the time resolution of the rain gauge data. When projected on the ground, the leading edge of this 1200-m swath along the cell track was selected to be 200 m from the rain gauge. This allowed time, about 50 s at 4 m s^{-1} cell speed, for the largest precipitation particles from the leading edge of the swath to reach the ground at the rain gauge site. Changing the location of the leading edge to be 100 or 300 m from the rain gauge resulted in minor fluctuations (within $\pm 5\%$ for CHILL and $\pm 2\%$ for CP-2) in the estimates of R . The data obtained from each of the lowest elevation angle PPI scans in this manner were placed at a time 200 s later than the time of the PPI scan. The 200 s corresponds to the time the center of the 1200-m swath reaches the rain gauge location.

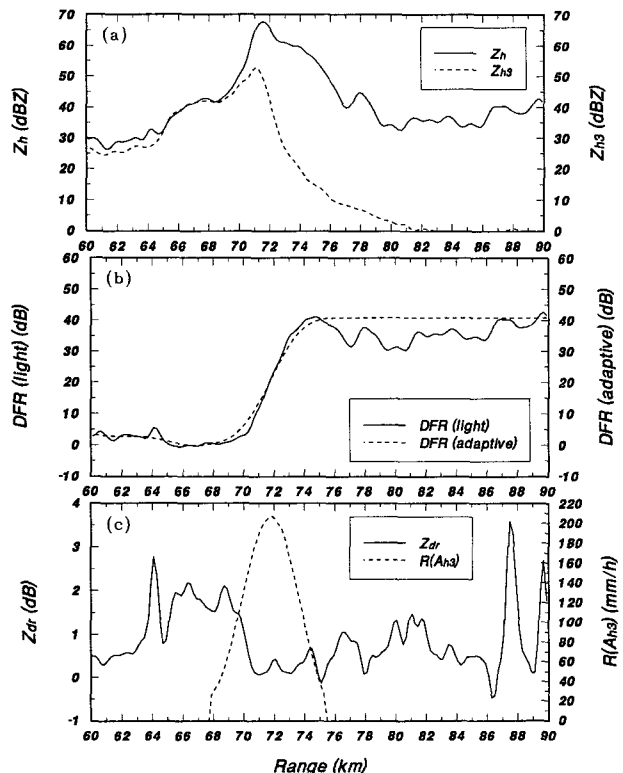


FIG. 3. Range profiles of (a) Z_H (S band) and Z_{H3} (X band), (b) D_{FR} (both lightly and adaptively filtered versions), and (c) Z_{DR} and $R_{A_{H3}}$, from a CP-2 radar ray through the storm system shown in Fig. 1, at time 1535:54 MDT 24 June 1992, and with elevation and azimuth angles being 0.6° and 6.2° , respectively.

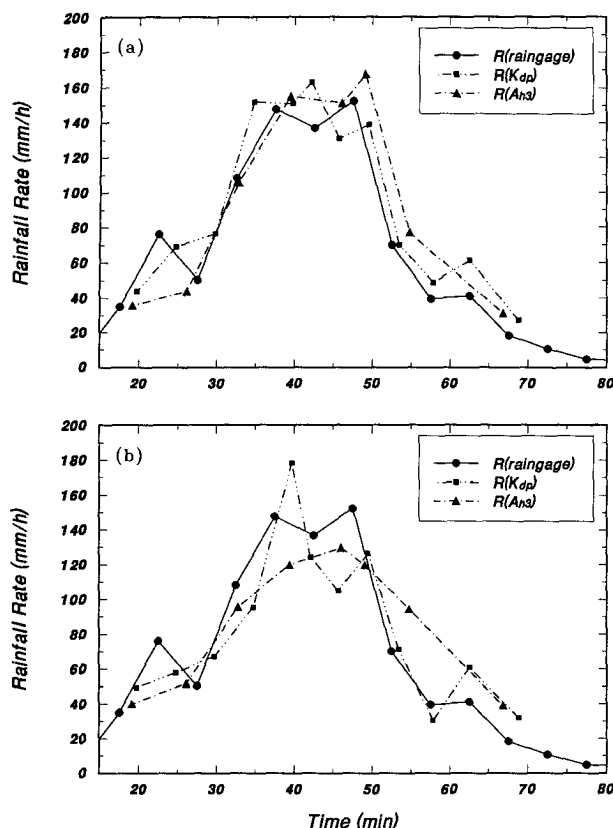


FIG. 4. Rainfall rates measured by the rain gauge and estimated from radar measurements of K_{DP} and A_{H3} using (a) method 1 and (b) method 2. The time axis corresponds to minutes after 1500 MDT.

The CP-2 radar scanned this storm during the entire rainfall event recorded by the rain gauge. However, the CHILL radar began its scans at about 1536 MDT, more than 15 min into the event. This “lost” time period for the CHILL radar was recovered from the earliest scan at 1536 MDT by taking 1200-m sections along the cell track that had already passed over the rain gauge. This process invoked the assumption that the cell structure did not change significantly over the 15-min time period. Time-height contours of maximum reflectivity and specific attenuation from the CP-2 radar over a $2 \text{ km} \times 2 \text{ km}$ rectangular “box” centered over the rain gauge location and extending in height from 0.5 km to near storm top were examined for the storm duration (1517–1605 MDT). It was verified that the vertical storm structure was nearly the same for the 15-min period prior to 1536 MDT.

b. Method 2

In the second method used for comparing radar and rain gauge measurements of R , the range gate directly above the rain gauge was used. The data point for the

radar estimate of R was again shifted by 200 s, but this time in the opposite direction, that is, to an earlier time than the PPI scan time. For the CHILL data it was again necessary to extract all times prior to 1536 MDT by taking data along the part of the track in the earliest PPI scan that already passed over the rain gauge location.

c. Results

Figure 4a shows the rain gauge measurements of R together with R_{KDP} and R_{AH3} obtained by method 1. These results indicate that R_{KDP} and R_{AH3} are in good agreement with the rain gauge measurements. Even the less sophisticated method—method 2—produced good results as seen in Fig. 4b. Figure 5 shows the rainfall rates obtained from the R - Z relation of Eq. (3), where Z_H is truncated at 50, 55, and 60 dBZ. It is clear that the 55-dBZ truncation produces the best R - Z result for this case, and to our knowledge appears to be in use for the Denver WSR-88D. However, this cannot be generalized to all storms without significant error as the truncation point will depend on hail rate and maximum hail diameter. For example, Balakrishnan

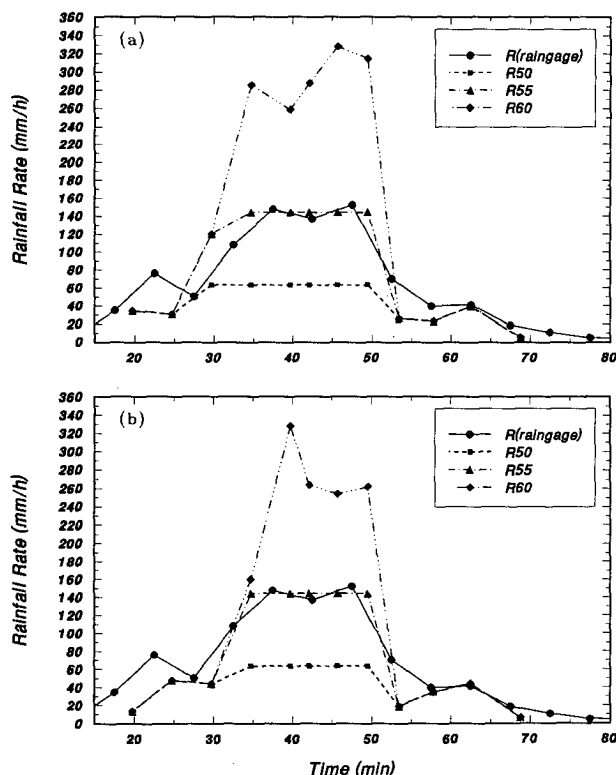


FIG. 5. Rainfall rates measured by the rain gauge and estimated from radar measurements of Z_H , which was truncated at 50-, 55-, and 60-dBZ peak values, using (a) method 1 and (b) method 2. The time axis corresponds to minutes after 1500 MDT.

TABLE 1. Rainfall accumulation (Σ) obtained from Figs. 4 and 5 and their difference relative to the rain gauge (Δ).

	Rain gauge	Method 1					Method 2				
		K_{DP}	A_{H3}	$Z_H(50)$	$Z_H(55)$	$Z_H(60)$	K_{DP}	A_{H3}	$Z_H(50)$	$Z_H(55)$	$Z_H(60)$
Σ (mm)	73.3	79.7	77.5	38.6	69.3	117.5	70.2	72.4	37.6	63.5	96.5
Δ (%)	0	9	6	-47	-5	60	-4	-1	-49	-13	32

and Zrnić (1990) provide model results for mixed precipitation composed of raindrops and wet, dry, or spongy hail using the Cheng and English (1983) hail size distribution model with minimum and maximum hail diameters of 3.75 and 60 mm, respectively. Their results show that for a constant "spongy" hailfall rate of around 10 mm h^{-1} , the Z_H is constant at 55 dBZ even when rain rate increases from zero to 50 mm h^{-1} (the upper rain-rate value varies from 30 to 130 mm h^{-1} depending on dry or wet hail model).

An important parameter of a rain event is the rainfall accumulation. Table 1 presents the accumulation results from the various estimation methods presented in Figs. 4 and 5. It is seen that both K_{DP} and A_{H3} produce accumulation values within 10% of the rain gauge measurements. The R - Z relation with Z_H truncated at 55 dBZ also produces good results, -5% with method 1 and -13% with method 2. Truncating Z_H at 50 or 60 dBZ increases the relative errors dramatically, up to -47% and 60% with method 1 and -49% and 32% with method 2, respectively.

5. Conclusions

This paper demonstrated the capability of K_{DP} for estimating rainfall rates in a severe storm with rainfall accompanied by hail. The radar estimates of R were compared with measurements from a ground-based rain gauge. In addition to the R - K_{DP} relation, R - A_{H3} and R - Z relations were also tested. Both K_{DP} and A_{H3} produced rainfall rates in good agreement with the rain gauge measurements. The rainfall accumulation estimates were within 10% of the rain gauge value. With the R - Z relation, the best results were obtained when Z_H was truncated at 55 dBZ. However, truncating Z_H at 50 or 60 dBZ produced poorer results. It is worth noting that K_{DP} and A_{H3} are independent of the radar system gain, unlike Z_H , and as a result will not be biased by such uncertainties, which can easily exceed 1 dB. Furthermore, K_{DP} is sensitive to raindrops that are highly aligned with oblate shapes, and is not so sensitive to irregularly shaped or tumbling hailstones. These aspects of K_{DP} make it attractive for estimating R in the presence of hail and can potentially serve as "ground truth" for evaluating rainfall accumulation algorithms based on R - Z techniques, for example, the NEXRAD precipitation algorithms.

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