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

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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_{XB} . These estimates were compared with measurements from a ground-based rain gauge. Both R - K_{DP} and R - A_{XB} 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.

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 (Manuscript received 21 February 1994, in final form 23 June 1994) ABSTRACT Multiparameter radar measurements were made during a heavy rainfall event accompanied by hail in Colorado. Rainfall rates R and accumulation Z for this event were estimated using S-band specific differential phase K_{DP} , reflectivity factor Z_h , and X-band specific attenuation A_m . These estimates were compared with measurements from a ground-based rain gauge. Both R - K_{DP} , and R - A_m 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_u , Z_{Da}) relations (Battan 1973; Seliga and Bringi 1976) can lead to significant errors. In the case of R - Z_u , 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_{tt} , Z_{OR}) relation is affected by this bias in Z_h as well as bias in 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 (10.9cm wavelength) radar rainfall estimation in the presence of hail using one-way specific differential phase K_{ov} between H and V polarizations compared with a ground-based rain gauge. One-way specific attenuation A_{te3} at X band (3.2-cm wavelength) is used as another

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Kultegin Aydin, Department of Electrical Engineering The Pennsylvania State University, University Park, PA 16802. estimator of R for comparison with the rain gauge in the same rainfall event. Both K_{vv} and Z_{dr} are forward scattering parameters as opposed to Z_h and Z_{oh} , 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_m 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_s is at S band. The main drawback of A_m 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 $R = 37.1 K_{dp}^{0.5}$ (Sachidananda and Zrnić 1987), and $R = 36.1 - 0.54 K_{dp}^{0.7}$ for $0.01 < K_{dp} < 1.5$ -km⁻¹ and $33.77 / K_{dp}^{0.7}$, for $1.5 < K_{dp} < 7$ -km⁻¹ (Aydin and Giridhar 1992), which are termed the SZ and AG relationships, respectively. Here we use the relationship (Chandrasekar et al. 1990) $R_{0.5} = 40.5 K_{dp}^{0.5}$ (mm h⁻¹), (1) c 1995 American Meteorological Society FEBRUARY 1995 AYDIN ET AL. 405 where K_{dp} has units of degrees per kilometer. The parameters a and b of the relation $R_{KDP} = a K_{dp}^b$ 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 $N_0 = 8000$ m⁻³ mm^{-t}. 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

$Z < R < 200 \text{ mm h}^{-1}$ 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_m) 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: $R \sim 0.84 A_m^{1/3}$ (mm $\text{h}^{-1} = 0.84 A_m^{1/3}$), (2) where A_m is in decibels per kilometer. The next section describes how K_{VV} and A_m are estimated. Both estimators are insensitive to the absolute gain of the radars (Doviak and Zrnic 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) $R_z = 0.017 Z^{0.714}$ (mm h^{-1}), (3) where Z is in its standard units ($\text{mm}^6 \text{ m}^{-3}$). This ZR 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_r , with Z_r and K_r 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_r hail signature indicates a hail core at about (-39, 16) km, where $Z_r > R < 0.5 \text{ dB}$ and $Z_n > 60 \text{ dBZ}$. In fact the entire region with $Z_n > 45 \text{ dBZ}$ and $Z_r > R < 0.5 \text{ dB}$ 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 $Z_n > 50 \text{ dBZ}$ contour, one of which is in the hail region described above, the peak K_{DP} being 3.6- km^{-1} at (-38, 16) km. The high values

of K_{r-v} 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_u , K_{Dp} , $-DP$ (two-way propagation differential phase shift), Z_{DR} , and R_{KDe} along a ray. The Z_{-} , $Z_{r>R}$, and $-D_v$ 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 $-DP$ 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 $-D_e$, $K_{r-p} = [q_b D_p(r_2) - q_b D_p(r_1)] / [2(r_2 - r_1)]$, where $2(r_2 - r_1) = 300$ m. The resulting K_{Dv} accuracy is estimated to be within ± 0.5 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_{Dv} as ± 0.25 km $^{-1}$ in conditions of very high ρ_{hv} (>0.985) and using 128 sample H-V pairs in the estimate of $-D_v$ at any one resolution volume. We have degraded this accuracy here by a factor of 2 to account for lowered ρ_{rv} 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_{-} is very high and exceeds 55 dBZ, indicating the presence of hailstones. The rainfall rate R_{Kvp} estimated from K_{r-p} is above 190 mm h $^{-1}$ in this core. Figure 3 shows CP-2 radar measurements of Z_u (S band), Z_{n3} (X band), Z_{r-R} (S band), dual-frequency ratio $DFR = Z_n - Z_{n3}$ (dB), and R_{An3} along a ray. The rain gauge is located at 8.2 $^\circ$ 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 $q_{r>v}$. The specific attenuation A_{n3} is calculated as one-half the slope of the adaptively filtered DFR just as K_{r-p} is obtained from $-D_v$. The accuracy in

An3 is es 406 JOURNAL OF APPLIED METEOROLOGY 30,0 VOLUME 34 40.0
 50.0 60.0 $z \sim$ (deZ) 2.0 Zdr 0.5 3.5 Kdp timated to be +0.5 dB km-], 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 AH3
 should be zero (Liu et al. 1993). Note the intense attenuation at X band as seen
 in the dramatic reduction of ZH3 relative to ZH as the beam penetrates the core
 at about 71 km. The rainfall rate RAH3 estimated from AH3 exceeds 200 mm h⁻¹
 in this core. Differential reflectivity ZDR in the core is less than 0.5 dB whereas
 ZH 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 FIG. 1. Constant-altitude ($Z =$
 1.5 km AGL) PPI section from CSU-CHILL radar located at grid origin. The
 Xdistance (Y distance) refers to distance (kin) west (north) of the radar. (a)
 Reflectivity ZH (dBZ), (b) ZDR (dB) with ZH contours starting at 30 dBZ and
 incrementing by 10 dB, (c) KDp (- km-l) with same $Z \sim$ contours. The rain gauge is
 located on the CSU campus at (-37.7, 15.3) kin. 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 ___ 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 ram. 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

FEBRUARY 1995 AYDIN ET AL. 407 ~ so s ' ,,,,,,;,,;,,;? : .. ~ 4)~ OlghO s (~) /" , , ~ ~ ,,~ ~ '~ F~G. 2. Range profiles of {a) Z~ and K~, (b) -~ (both lightly and adaptively filtered versions), and (c) Z~ and R~, 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 KDP 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 (___0.5 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 CSUCHILL 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 +5% for CHILL and +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.

Figure 3 shows the range profiles of (a) Z_s (S band) and Z_x (X band), (b) DFR (both lightly and adaptively filtered versions), and (c) Z_s and R_m, from a CP-2 radar ray through the store 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.

Figure 4a shows the rain gauge measurements of R together with RKDP and RAM obtained by method 1. These results indicate that RKDP and R_{nn3} are in good agreement with the rain gauge measurements. Even the less sophisticated 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_n 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 30 40 SO 60 70 80 360 Time (rain) FIG. 4. Rainfall rates measured by the rain gauge and estimated from radar measurements of Kpe and Am 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 km x 2 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 i i i ~ i i , ~ j 1 S40 (~) *. S~O - ~ R(rain gauge) 300 / '~'. '-.-- RSO 2aO .~ i -,*- R\$5 ~ ~o ~ ~ .~ - R60 240 : ~ ~o ~ i ~ ~0 / ~ ~ ~ I' ~ 160 - 140 ~ / ~ - ~ ~ : ,~ ~ ,oo, ~0 /' -~, 40 20 0 20 30 40 50 60 70 80 380 , , , , ~ , S40 (b) ~ ~20 ~ - R(r~ngage) .. ~00 I '~ '-~-- RSO 280 - ~ -. R55 ~ ~ ' ~- ~o E 240 / ~ 220 / ~ ~ ~o / ~ ~0 ~ ~ ~0 ~ ~ ~ 140 .:~~, ~ ~ . ~ ~ ~ ~o ~ ~ ~ ~0 ~0 0 20 30 40 50 60 70 80 Time (min) FIG. 5. Rainfall rates measured by the rain gauge and estimated from radar measurements of Z~, which was truncated at 50-, 55-, and 60-dBZ peak values, using (a) method 1 and (b) method 2. The time axis co~espon~ to minutes after 1500 MDT. FEBRUARY 1995 A Y D I N E T A L. TABLE I. Rainfall accumulation (Z) obtained from Figs. 4 and 5 and their

difference relative to the rain gauge (Δ). 409 Method 1 Method 2 Rain gauge
 KDV AH3 Z/q(50) Z/~55) Zn(60) KDv Au3 Z/q(50) Z/q(55) Zu(60) (mm) 73.3 79.7
 77.5 38.6 69.3 117.5 70.2 72.4 37.6 63.5 96.5 (%) 0 9 6 -47 -5 60 -4 -1 -49 -13
 32 and Zrnifi (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~ 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 KDp
 and AH3 produce accumulation values within 10% of the rain gauge
 measurements. The R-Z relation with Z~ truncated at 55 dBZ also produces good
 results, -5% with method 1 and -13% with method 2. Truncating Zu 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 gDp 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-KDp
 relation, R-A~3 and R-Z relations were also tested. Both KDp and An3 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~ was truncated at 55 dBZ.
 However, truncating Z~ at 50 or 60 dBZ produced poorer results. It is worth
 noting that KDp and A~3 are independent of the radar system gain, unlike Zn,
 and as a result will not be biased by such uncertainties, which can easily exceed
 1 dB. Furthermore, KDp 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 KDV 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. Acknowledgments. This research was supported by the National Science Foundation (NSF) Grant ATM9225116 and the Army Research Office Contract DAAL03-89-K-0158 at The Pennsylvania State University. During the course of this research Dr. K. Aydin was at CSU on sabbatical leave from Penn State. The CSU-CHILL radar is a national facility supported by the NSF Grant ATM-8919080. Dr. Li Liu was supported by the NSF Grant ATM-9014600. The CP-2 radar data were acquired as part of RAPS092 field program and were made available to the authors courtesy of Drs. Brandes and Vivekanandan of NCAR/Research Applications Division. The rain gauge data were supplied by Mr. N. Doeskin, Assistant State Climatologist at the Colorado Climate Center. The authors also acknowledge the assistance rendered by Mr. Patrick Kennedy of the CSU-CHILL radar facility.

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