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THE QUALITY OF RAINFALL ESTIMATION WITH THE POLARIMETRIC WSR-88D RADAR AS A FUNCTION OF RANGE

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1. INTRODUCTION

Accurate rainfall estimates are vital for several hydrologic applications. The National Weather Service requires estimating rainfall at ranges up to 230 km from the radar. Rainfall estimates at large distance are especially important in regions with limited radar coverage. Having reliable rain estimates over large distances is also beneficial for validation of satellite observations since these are usually characterized by rather wide swaths.

Increased distance from the radar is often associated with a degradation of accuracy among conventional R(Z) relations. Range-related errors may be significant, particularly during cold season events associated with low melting layers. Range dependence is also attributed to overshooting of precipitation, beam geometry such as beam broadening and filling, radar signal sensitivity losses, and drop size distribution (DSD) evolution in the vertical which can produce illuminated volume characteristics bearing little resemblance to the near-surface scatterers.

While some studies discuss the quality of conventional radar rain measurements at large distances (e.g., Smith et al. 1996, Seo et al. 2000), the performance of polarimetric methods at distances greater than 100 km is not well investigated. With few exceptions, the majority of the dual-polarization S-band radar - gauge comparisons were made for warm season precipitation and at distances less than 100 km. These validation studies have shown that at close distances from the radar (a) there is an improvement in rainfall estimation if a dual polarization radar is used and (b) polarimetric rainfall estimation techniques are more robust with respect to DSD variations than are conventional R(Z) relations. It is not clear if these advantages of dual polarization radar hold at larger distances from the radar.

As part of the evolution and future enhancement of the WSR-88D, the National Severe Storms Laboratory recently upgraded the KOUN WSR-88D radar to include polarimetric capability. In this paper, we assess the quality of rainfall estimation for a broad range of distances. 108 Oklahoma Mesonet gauges are used to validate the results of radar rain measurements. These gauges are located at distances between 25 and 290 km from the KOUN radar.

2. RADAR DATA SET

Data collection with the WSR-88D KOUN prototype dual-polarization radar started on 19 March, 2002. Since then, the polarimetric data have been collected and archived for about 80 days of observation. Ancillary data from the operational KTLX WSR-88D radar have been collected for the majority of the precipitation events. We have selected for in-depth analysis a subset of 15 rain events with 52 hours of observation for which Oklahoma Mesonet gauges recorded a sizable amount of precipitation. This subset consists of 7 convective and 8 stratiform rain cases observed from August 2002 to May 2003.

Differential reflectivity Z_{DR}, specific differential phase K_{DP}, conventional radar reflectivity factor Z, and correlation coefficient ρ_{hv} were measured using dwell time, resolution, and volume coverage patterns (VCP) outlined in Ryzhkov et al. 2003. Data are thresholded using ρ_{hv} to filter out echoes of non-meteorological origin, and radar reflectivity factor is calibrated using techniques outlined in Ryzhkov et al. 2003. A Z threshold of 53 dBZ is applied to mitigate hail contamination. For most cases, KOUN reflectivity factor is expected within 1 dB of the well-calibrated KTLX radar.

The study compares one-hour rain totals obtained over Oklahoma Mesonet gauges located within 250 km of the KOUN radar. Hourly point estimates are defined as an hourly total rainfall accumulation averaged over an area centered on an individual gauge. We average radar rainrates from 5 gates centered on the gauge and the two closest azimuths. This produces a radial resolution of 1.3 km and variable transverse resolution (1 - 5 km).

To determine the quality of different polarimetric rain algorithms, absolute differences between radar and gauge estimates (expressed in mm) are examined rather than standard fractional errors which are heavily weighted with small accumulations. Rainfall estimates are characterized by the bias $B = \langle\Delta\rangle$, standard deviation $SD = \langle|\Delta - B|^2\rangle^{1/2}$, and the rms error $RMSE = \langle|\Delta|^2\rangle^{1/2}$, where $\Delta = T_R - T_G$ is the difference between radar and gauge hourly totals for any given radar-gauge pair and brackets imply averaging over all such pairs.

3. RAINFALL ALGORITHMS AND THEIR PERFORMANCE

The performance of rainfall relations for the region encompassed by Oklahoma Mesonet gauge locations is assessed using rainfall algorithms of different types: R(Z), $R(K_{DP})$, $R(Z,Z_{DR})$, $R(K_{DP},Z_{DR})$, and $R(Z,K_{DP},Z_{DR})$. From each algorithm type, we selected the one that

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performed the best over the ARS micronetwork located 50 – 90 km from the KOUN radar (Ryzhkov et al. 2003):

$$R(Z) = 1.7\ 10^{-2}\ Z^{0.714}, \quad (1)$$

$$R(K_{DP}) = 45.3|K_{DP}|^{0.786}\mathrm{sign}(K_{DP}), \quad (2)$$

$$R(Z,Z_{DR}) = 1.42\ 10^{-2}\ Z^{0.770}\ Z_{dr}^{-1.67}, \quad (3)$$

$$R(K_{DP},Z_{DR}) = 136|K_{DP}|^{0.968}\ Z_{dr}^{-2.86}\ \mathrm{sign}(K_{DP}), \quad (4)$$

where Z is expressed in mm^6m^{-3}, rainfall rate R in mm h^{-1}, K_{DP} in deg km^{-1}, and Z_{dr} is the differential reflectivity expressed in linear units. A "synthetic" algorithm $R(Z,K_{DP},Z_{DR})$ is also applied to the data so that

if $R(Z) < 6$ mm h^{-1}, then

$$R = R(Z)/(0.4+5.05\ (Z_{dr} - 1)^{1.17}); \quad (5)$$

If $6 < R(Z) < 50$ mm h^{-1}, then

$$R = R(K_{DP})/(0.4+3.48\ (Z_{dr} - 1)^{1.72}); \quad (6)$$

If $R(Z) > 50$ mm h^{-1}, then $R = R(K_{DP})$,

where R(Z) and $R(K_{DP})$ are determined by Eq (1) and (2).

3.1 Comparison Between ARS and Mesonet Results at Close Distance to the Radar

As an initial step, we examine the performance of these five algorithms at close distance (<100km) from the radar to check the consistency with results obtained for the dense ARS micronetwork (Ryzhkov et al. 2003). Only Mesonet gauges located within 100 km were selected. The areal coverage discrepancy between these networks is substantial, therefore only point estimates for these networks are compared (Table 1).

As can be seen in Table 1, the results obtained for the different gauge networks do not differ substantially. Similar to the results presented for the ARS network in Ryzhkov et al. 2003, the $R(Z,K_{DP},Z_{DR})$ "synthetic" algorithm shows superior performance and outperforms the R(Z) relation by a factor of 1.5 in RMSE. All polarimetric relations outperform the conventional R(Z) relation by at least a factor of 1.3 for SD and RMSE. Bias values for the Mesonet are also similar to Ryzhkov et al. 2003.

3.2 Performance of Rainfall Relations for Select Range Intervals

Figure 1 shows mean bias and RMS errors of the different radar rainfall estimates in the range interval 50-225 km. Intervals of 50 km in range, centered at 25 km increments beginning with a range of 50 km, have been selected for this analysis. 52 hours of observation from all available gauges within 250 km are represented in these statistics. There are a total of 1515 hourly comparisons from 25-250 km.

Polarimetric algorithms outperform the conventional R(Z) relation to approximately 125-150 km from the radar. The improvement is typically by a factor of 1.25-1.5 for the best available polarimetric estimates in RMSE and better than a factor of 1.2 in RMSE for all polarimetric rainfall estimates within 100 km.

The polarimetric estimates exhibit a negative bias, whereas the R(Z) relation gives positively bias for all ranges. In a broad region between 125 and 200 km, all radar rainfall estimates tend to be positively biased with a sharp increase of the RMS error. This is primarily attributed to bright band contamination during cold season. At distances beyond 200 km, the performance of all algorithms rapidly deteriorates, likely due to overshooting.

3.3 "Cold Season" Rain Events

We noticed that the performance of all radar algorithms at large distances is affected by the presence/absence of the low bright band. Separate statistics were obtained for the "cold season" events for which bright band played a significant role and the "warm season" events which were not substantially affected by the bright band. The cold season subset contains 29 hours of observation from September through November 2002 (Figure 2). These events contain embedded convection, however they are best classified as widespread startiform precipitation and nocturnal MCS events.

Polarimetric relations outperform the R(Z) relation for all ranges examined. The influence of bright band contamination on rainfall estimates in the cold season is pronounced. All estimates exhibit a relative negative bias at close distances to the radar, relative overestimation in ranges consistent with the height of the melting layer, and relative underestimation at far distances consistent with overshooting precipitation, beam widening, and loss of sensitivity. The results for the R(Z) relation agree with Smith et al. 1996 as it pertains to the conceptual performance of the relation for cold season events.

Melting layer contamination is mitigated if the $R(K_{DP})$ relation is used. This estimate exhibits minimal bias between 125-200 km, and has the lowest RMSE and SD for any estimate.

At close distances (<100 km) unaffected by bright band contamination, the $R(Z,K_{DP},Z_{DR})$ algorithm outperforms the other relations.

Table 1. Mean biases, standard deviations, and RMS errors of the radar estimates of one-hour rain totals (in mm) for different radar rainfall algorithms. ARS values and Mesonet gauge values (<100 km) are listed.

Algorithm	MES Bias	MES SD	MES RMSE	ARS Bias	ARS RMSE
R(Z)	0.45	4.61	4.63	0.32	4.20
$R(K_{DP})$	-0.82	3.26	3.37	-0.55	3.68
$R(Z,Z_{DR})$	-0.82	3.40	3.49	-0.81	2.98
$R(K_{DP},Z_{DR})$	-1.35	2.77	3.08	-0.86	3.06
$R(Z,K_{DP}, Z_{DR})$	-0.63	2.94	3.01	-0.10	2.80

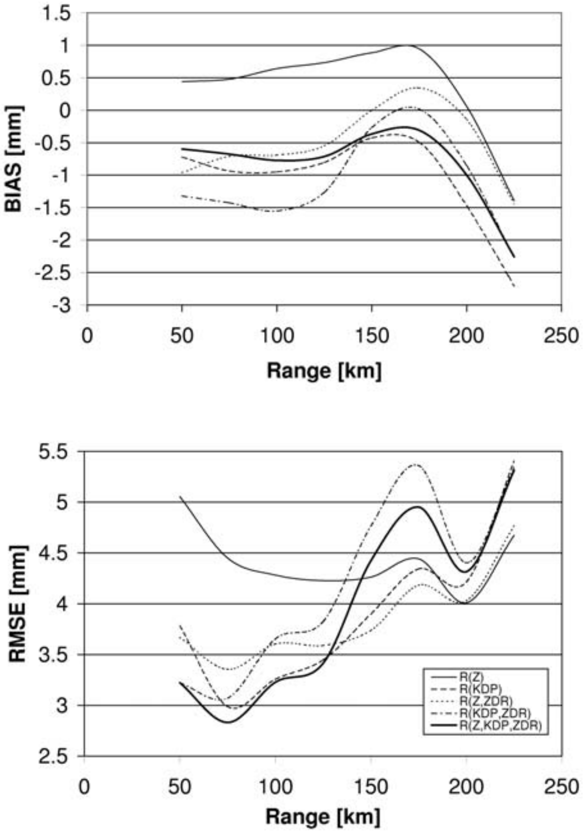

Figure 1. Mean biases and RMS errors of the radar estimates as functions of range. All 52 hours of observation are included in the statistics.

3.4 "Warm Season" Rain Events

The "warm season" subset includes 23 hours of observation from late April to mid-August 2002-2003 rainfall events (Figure 3). These events are best classified as ordinary convective lines with occasional supercell convection. Some of these events have significant portions of stratiform rain. Substantial hail was reported for several of the events examined. As described in Ryzhkov et al. 2003, several hours of data for this subset were collected using 6-minute update times, which may impact the magnitudes of the RMS errors.

Polarimetric relations show comparable results at close distances to the radar (<100 km). Polarimetric relations typically outperform the R(Z) relation by a factor of 1.4 in RMSE. R(Z) is apparently positively biased due to hail contamination.

At large distance from the radar, the RMS errors gradually increase and bias becomes more negative, consistent with overshooting of precipitation and widening of the radar beam. For warm season events, the R(Z) and R(Z,Z_{DR}) relations perform better than the K_{DP}-based algorithms at large distances from the radar.

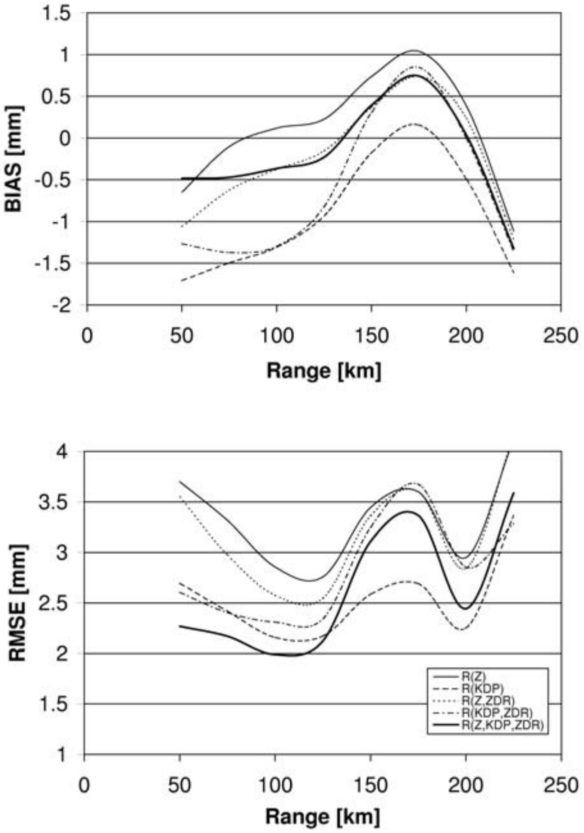

Figure 2. Mean biases and RMS errors of the radar estimates as functions of range for cold season events. 29 hours of observation are included in the statistics.

4. SUMMARY AND CONCLUSIONS

At relatively close distances from the radar (< 125 km) where bright band contamination is negligible, the quality of radar rainfall estimates is mostly determined by DSD variations and the possible presence of hail. As our analysis shows, these two problems are best addressed by the synthetic R(Z,K_{DP},Z_{DR}) algorithm. It combines merits of the Z-Z_{DR} pair for light rain, the K_{DP}-Z_{DR} combination for moderate-to-heavy rain, and capitalizes on relative insensitivity of K_{DP} to the presence of hail. All polarimetric methods outperform the conventional R(Z) algorithm in terms of RMS error. The R(Z) relation also tends to overestimate rain during warm season (mainly due to hail contamination) even if we threshold radar reflectivity factor at the level of 53 dBZ.

In the range interval 125 – 200 km, the bright band becomes a leading factor affecting the performance of all algorithms during cold season, when rain is predominantly stratiform and the melting level is quite low. At these distances, the synthetic algorithm is no longer superior because Z and Z_{DR} are substantially affected by melting hydrometeors. Surprisingly, the R(K_{DP}) algorithm is more immune to the bright band contamination than the others. It performs best of all, both in terms of bias and RMS error. The situation is very different in the warm season when rain is mostly associated with strong localized convection, rain fields are very non-uniform, and bright band contamination is not a key factor. Rain estimates based on K_{DP} rapidly degrade with distance. There are several reasons for such degradation.

First, there is possible folding of total differential phase Φ_{DP} at longer distances. The current RVP7 data processor enables unambiguous measurements of Φ_{DP} only up to 180°, and the unfolding procedure does not work well all the time. This problem will be fixed once the existing processor is replaced by the newer one (RVP8).

Second, differential phase suffers more than any other radar variables from the non-uniform beam filling that is exacerbated at longer distances. Strong gradients of Z or Φ_{DP} within the radar resolution volume cause oscillations in the otherwise monotonic range dependencies of Φ_{DP} and spurious negative / positive K_{DP} as a result. This is an unavoidable deficiency of K_{DP}.

Third, the radial resolution of K_{DP} estimates is worse than that of Z and Z_{DR}. When combined with poor azimuthal resolution at large distances, this issue might cause problems for point estimations of rainfall. These three factors might explain why the R(Z) and R(Z,Z_{DR}) algorithms outperform the K_{DP}-based algorithms during the warm season at far ranges.

At the ranges beyond 200 km, all radar algorithms for rainfall estimation perform equally poorly due to overshooting, beam broadening, and loss of sensitivity.

5. REFERENCES

Ryzhkov, A.V., S. Giangrande, and T.J. Schuur, 2003: Rainfall Estimation with a Polarimetric Prototype of the Operational WSR-88D Radar. *This volume.*

Seo, D. -J., J. Breidenbach, R. Fulton, D. Miller, T. O'Bannon, 2000: Real-Time Adjustment of Range-Dependent Biases in WSR-88D Rainfall Estimates due to Nonuniform Vertical Profile of Reflectivity. *Journal of Hydrometeorology*: Vol. 1, **3**, pp. 222–240.

Smith, J.A., D.-J. Seo, M.L. Baeck, and M.D. Hudlow, 1996: An Intercomparison of NEXRAD Precipitation Estimates. *Water Resour. Res.*, **32**, pp. 2035-2045.

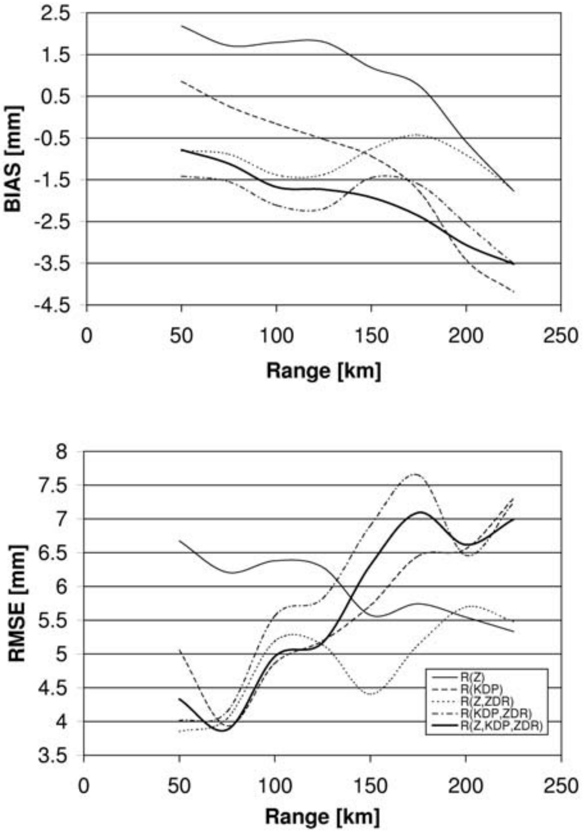

Figure 3. Mean biases and RMS errors of the radar estimates as functions of range for warm season events. 23 hours of observation are included in the statistics.