Testing a Polarimetric Rainfall Algorithm and Comparison with a Dense Network of Rain Gauges.

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ABSTRACT: The paper presents an analysis of the performance of different radar algorithms for rainfall estimation. These are the conventional one based on radar reflectivity factor Z and three polarimetric estimators utilizing different combinations of Z, specific differential phase K_{DP}, and differential reflectivity $Z_{DR.}$ A dense micronetwork of 42 gauges in central Oklahoma, USA, is used for validating the estimates of one-hour accumulations obtained from the nearby operational WSR-88D radar and Cimarron dual-polarization radar. Data set includes 13 storms with 39 hours of observations. An accuracy of point and areal radar rain measurements is assessed. Some radar calibration issues for both conventional and dual-polarization radar are addressed.

1. INTRODUCTION

Research studies of the past decade indicate that polarimetric weather radars provide good opportunities for improvement in rainfall measurements. These studies have shown that polarimetric rainfall estimation algorithm based on specific differential phase K_{DP} outperforms the conventional R(Z) method in the presence of hail contamination, partial radar beam blockage, attenuation in rain, and radar miscalibration (Zrnic and Ryzhkov 1999). Measurements of differential phase are especially beneficial at shorter wavelengths (at C or X band) for which attenuation is a major problem in heavy precipitation (May et al. 1999, Carey et al. 2000, Testud et al. 2000, Matrosov et al. 1999, 2001). The $R(K_{DP})$ estimator, however, is somewhat prone to drops size distribution (DSD) variations, although to a lesser degree than the conventional algorithm R(Z).

According to the data collected with the NSSL's Cimarron and the NCAR's S-Pol polarimetric radars in Oklahoma (Ryzhkov and Zrnic 1996) and Kansas (Brandes et al. 2001), both the R(Z) and $R(K_{DP})$ algorithms underestimate / overestimate rainfall if differential reflectivity Z_{DR} is unusually low / high. Thus, combined algorithms using joint measurements of K_{DP} and Z_{DR} or Z and Z_{DR} are called for to estimate rainfall more accurately.

As a part of preparatory work for the Joint Polarization Experiment (JPOLE) aimed at a transfer of polarimetric radar technology to an operational arena and scheduled for the years 2002 – 2003 in central Oklahoma, we analyzed the performance of different versions of polarimetric rainfall estimation algorithm using dense micronetwork of raingauges. In this study, we explore the utility of the $R(K_{DP})$, $R(K_{DP},Z_{DR})$, and $R(Z,Z_{DR})$ relations that have been "matched" with the 3-year statistics of DSDs obtained with a 2D-video-disdrometer in central Oklahoma (Schuur et al. 2001). We compare one-hour rain accumulations obtained from the Cimarron radar and 42 gauges comprising a dense micronetwork in the 40 x 30 km Little Washita River watershed basin.

2. EXPERIMENTAL FACILITIES AND RADAR CALIBRATION ISSUES

Rainfall estimation within the Little Washita River watershed basin was performed using the data from two radars: the operational Doppler WSR-88D radar (KTLX) and research dual-polarization Cimarron radar. Both radars operate at S band (10 – 11 cm wavelength). The WSR-88D radar was used mainly as a source of calibrated radar reflectivity data. It was found that the radar reflectivity factor measured by the Cimarron radar could be significantly biased due to partial blockage of the radar beam at the lowest elevation angle 0.5°, which is likely caused by nearby trees and a ridge in the direction to the gauge network area.

The gauges in the network are located at the ranges from 52 to 84 km with respect to the Cimarron radar and from 70 to 108 km with respect to the KTLX radar (Fig. 1). Average distance between gauges is about 4 – 5 km.

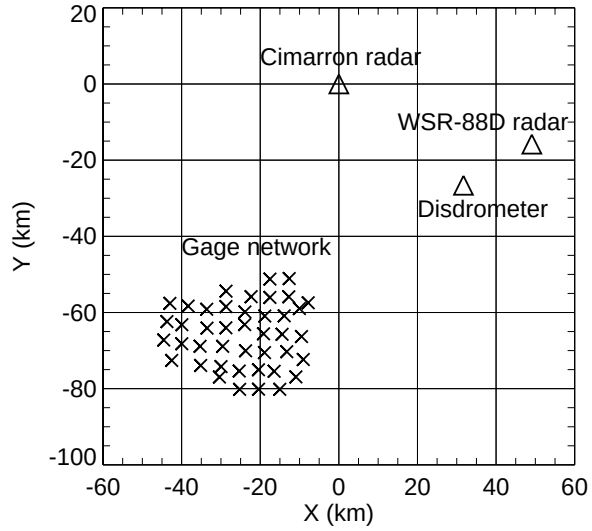

Figure 1. Location of the gauge network, Cimarron radar, WSR-88D radar, and 2D-video-disdrometer.

In addition to the radars and gauges, we used 2D-video-disdrometer located near the NSSL building in Norman to study DSD variations in precipitation.

As mentioned before, the Cimarron radar beam at the elevation of 0.5° is partially blocked in the azimuthal sector corresponding to the gauge network. This results in a significant negative bias in the radar reflectivity factor Z. This bias varies with azimuth and changes from storm to storm. Beam blockage affects differential reflectivity as well. To assess azimuthal variability of the Z and Z_{DR} biases, we capitalize on specific differential phase K_{DP}, which is immune to the blockage. Examination of K_{DP} – Z and K_{DP} – Z_{DR} scattergrams for each particular storm as function of azimuth allows to obtain azimuthal dependencies of the Z and Z_{DR} biases (ΔZ and ΔZ_{DR} respectively). Fig. 2 illustrates the dependencies of ΔZ and ΔZ_{DR} on azimuth in the sector 180 - 225° for the rain event on October 21, 2000.

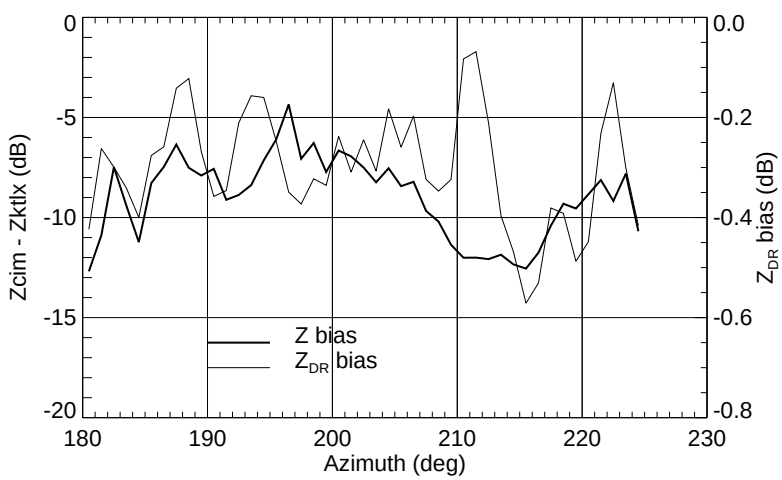

Figure 2. Azimuthal dependencies of the Z and Z_{DR} biases due to radar beam blockage in the sector containing gauge micronetwork for the 20 October 2000 case.

The curve for ΔZ is in good agreement with the results of direct comparisons of radar reflectivities measured with the Cimarron and WSR-88D radars. Fig. 2 shows that reflectivities measured by the Cimarron radar were 5 to 12 dB (depending on azimuth) lower than the ones obtained from the reference radar. Differential reflectivity bias varied between –0.6 and –0.1 dB.

In view of this, we decided not to use radar reflectivities measured by the Cimarron radar in our analysis and switch to Zs from the KTLX radar for the R(Z) rainfall estimation. Correction of Z_{DR} was performed on the basis of $Z_{DR} - K_{DP}$ consistency. Details of the correction technique are beyond the scope of this paper.

3. METHODOLOGY OF RAINFALL ESTIMATION

Four algorithms were used for radar rainfall estimation:

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

which is the standard one employed for WSR-88D,

$$R(K_{DP}) = 42.8\,|\,K_{DP}\,|^{0.802}\ \mathrm{sign}(K_{DP}), \tag{2}$$

$$R(K_{DP}, Z_{DR}) = 53.7\,|\,K_{DP}\,|^{0.910}\ Z_{DR}{}^{-0.421}\mathrm{sign}(K_{DP}) \tag{3a}$$

if $Z_{DR} > 0.5$ dB or

$$R(K_{DP}, Z_{DR}) = 70.0\,|\,K_{DP}\,|^{0.878}\ 10^{-0.131\,Z_{DR}}\ \mathrm{sign}(K_{DP}) \tag{3b}$$

if $Z_{DR} < 0.5$ dB,

$$R(Z, Z_{DR}) = 6.42\,10^{-3}\ Z^{0.824}\ Z_{DR}{}^{-0.654} \tag{4a}$$

if $Z_{DR} > 0.5$ dB or

$$R(Z, Z_{DR}) = 1.39\,10^{-2}\ Z^{0.813}\ 10^{-0.266\,Z_{DR}} \tag{4b}$$

if $Z_{DR} < 0.5$ dB.

In (1)-(4) Z is a radar reflectivity at horizontal polarization expressed in $mm^6\ m^{-3}$, K_{DP} is in deg km^{-1}, Z_{DR} is in dB. Algorithms (3a) and (4a) are not robust at low Z_{DR}, therefore, we switch to relations (3b) and (4b) which are more stable with respect to Z_{DR} measurement errors if Z_{DR} is close to zero. The relations (2) - (4) were derived for the Cimarron radar wavelength of 10.97 cm using the 3-year statistics of DSDs measured with the 2D-video-disdrometer and assumption of equilibrium raindrop shape given by Beard and Chuang (1987).

The data set includes rain events observed simultaneously by both radars since July 1997 when high-quality digital raingauge data became available for the network. This study presents a summary for 13 events that have been examined so far. Most of these events fall outside of the months typically associated with the heaviest convective rain in Oklahoma (May and June). Cool season rain events (during the September – November and February – April periods) have been known to produce outliers in both conventional and polarimetric rainfall estimation. 39 hours of rain have been examined altogether.

Five-minute tipping bucket gauge accumulations were used to compute hourly totals. In order to assess the performance of the algorithms (1) - (4) for different rain intensities, we separate contributions from light, moderate, and heavy rain for every one-hour accumulation estimated from the radar and measured by the gauges. Here, we classify rain as light if $R < 5$ mm h^{-1}, moderate if $5 < R < 30$ mm h^{-1}, and heavy if $R > 30$ mm h^{-1}. Along with hourly totals for individual gauges, we estimate "areal mean rain rate" as a sum of hourly totals from all 42 gauges divided by the number of gauges that recorded any rain. Thus, 39 estimates of areal mean rain rates have been obtained for 13 rain events.

4. SUMMARY OF RESULTS

Tables 1 – 4 and Fig. 3 summarize results for our data set. Tables 1 – 4 contain mean biases and standard deviations of the one-hour rain accumulation estimates for individual gauges and the whole test area. Instead of using standard fractional errors, which are heavily weighted by small accumulations, we prefer to examine absolute differences between radar and gauge estimates as a measure of the algorithm's

quality. Table 1 presents results for all rain intensities, whereas Tables 2 – 4 describe statistics for contributions from heavy, moderate, and light rain separately.

Table 1. Mean biases and standard deviations of the radar estimates of one-hour rain totals (in mm) and areal mean rain rates (in mm h^{-1}) for different radar rainfall algorithms.

Algorithm	**Individual gauges**		**Areal mean rain rate**	
	mean	stddev	mean	stddev
R(Z)	-0.55	4.49	-0.59	3.05
$R(K_{DP})$	-0.98	3.32	-1.01	1.77
$R(K_{DP}, Z_{DR})$	-0.34	3.19	-0.38	1.49
$R(Z, Z_{DR})$	0.43	4.95	0.36	3.52

Table 2. Same as in Table 1 but for heavy rain only

Algorithm	**Individual gauges**		**Areal mean rain rate**	
	mean	stddev	mean	stddev
R(Z)	3.39	6.45	1.88	3.86
$R(K_{DP})$	-0.44	3.93	-0.49	2.06
$R(K_{DP}, Z_{DR})$	-0.40	3.74	-0.41	1.88
$R(Z, Z_{DR})$	2.97	7.10	1.72	4.34

Table 3. Same as in Table 1 but for moderate rain only

Algorithm	**Individual gauges**		**Areal mean rain rate**	
	mean	stddev	mean	stddev
R(Z)	-0.41	2.65	-0.44	1.69
$R(K_{DP})$	-0.62	2.25	-0.58	1.22
$R(K_{DP}, Z_{DR})$	-0.16	2.10	-0.17	0.97
$R(Z, Z_{DR})$	0.43	3.18	0.31	2.13

Table 4. Same as in Table 1 but for light rain only

Algorithm	**Individual gauges**		**Areal mean rain rate**	
	mean	stddev	mean	stddev
R(Z)	-0.85	1.30	-0.82	0.92
$R(K_{DP})$	-0.52	1.51	-0.50	0.97
$R(K_{DP}, Z_{DR})$	-0.19	1.62	-0.18	0.96
$R(Z, Z_{DR})$	-0.39	1.30	0.38	0.96

It is obvious from Table 1 that the $R(K_{DP}, Z_{DR})$ algorithm is the best both for local and areal estimates. This was expected from the simulations based on the DSD statistics in central Oklahoma (Schuur et al. 2001). K_{DP}-based relations are especially well suited for areal rainfall estimation as the two right columns in Table 1 suggest. The use of the best of polarimetric algorithms, $R(K_{DP}, Z_{DR})$, results in more than two times reduction in the standard deviation of the areal accumulation estimate compared to the standard R(Z) method.

The $R(K_{DP})$ algorithm has the largest mean bias for both point and areal rain estimation. This negative bias might be attributed to a more spherical shape of raindrops than suggested by Beard and Chuang (1987)

and / or to the effect of drop canting. Andsager et al. (1999) indicated that oscillating drops have lower oblateness than equilibrium drops. The rms width of canting angle distribution σ = 10 - 15° results in the 6 – 13 % decrease of K_{DP} (Ryzhkov 2001). It can be shown that the mean bias in the $R(K_{DP})$ estimate almost vanishes if the intercept coefficient in the relation (2) is increased by 15%. The $R(K_{DP}, Z_{DR})$ relation is less susceptible to the drop shape and canting angle variations (Schuur et al. 2001). This results in better performance of the latter algorithm both in terms of bias and standard deviation.

It is evident from Tables 2 – 4 that the K_{DP}-based algorithms are much better than R(Z) and $R(Z,Z_{DR})$ for the heavy rain category. The non-polarimetric R(Z) relation, currently used on the WSR-88D, noticeably overestimates rainfall for heavy precipitation (most likely due to hail contamination and big drops supported by ice cores inside) and underestimates rain for light precipitation with R < 5 mm h^{-1}.
In the presence of hail, differential reflectivity drops, and this inevitably causes overestimation of rain if Z_{DR}- based algorithms are used. Differential attenuation is another factor that induces negative bias in $Z_{DR.}$ Thus, the relation $R(K_{DP}, Z_{DR})$ can be applied with confidence only after hail contaminated regions are identified and a correction is made for differential attenuation. The $R(K_{DP})$ relation probably should be utilized instead of $R(K_{DP}, Z_{DR})$ in the areas of hail and hail/rain mixture.

As can be seen from Tables 3 and 4, the $R(K_{DP})$ and $R(K_{DP}, Z_{DR})$ algorithms outperform both Z-based algorithms for moderate rain, but exhibit no advantage for rain intensities lower than 5 mm h^{-1}. This is caused primarily by increased noisiness of the K_{DP} and Z_{DR} data for lighter rainfall. At lower rain rates, K_{DP} becomes extremely sensitive to uncertainty in the shape of raindrops, which are usually quite small in drizzle-type rain. Thus, optimal rain measurement algorithm probably should utilize the $R(K_{DP}, Z_{DR})$ relation for moderate and heavy rain and the $R(Z,Z_{DR})$ or even R(Z) relation for light rain.

Fig. 3 displays biases in areal rainfall estimates for all four methods as a function of hour of observation ranked in the chronological order. First hour of observation dates back to 23 September 1997, whereas the last hour (out of total 39) corresponds to the 23 February 2001 rain event. An obvious temporal trend in the error for the R(Z) and $R(Z, Z_{DR})$ estimates is quite suspicious. No such trend is evident for the K_{DP}-based algorithms. This might indicate possible miscalibration of the operational WSR-88D radar that slowly progresses with time. Such a calibration error adversely affects the performance of both Z-based estimators. Regardless of miscalibration, several outliers of different signs evident in the R(Z) estimate in Fig. 3a are substantially reduced if the relation $R(K_{DP}, Z_{DR})$ is applied (Fig. 3c). These observations stress the need for long-term statistics of radar – gauge comparison over a fixed network of gauges and emphasize advantage of polarimetric rainfall estimates that are more reliable than the conventional ones even if the radar operates in severe blockage environment.

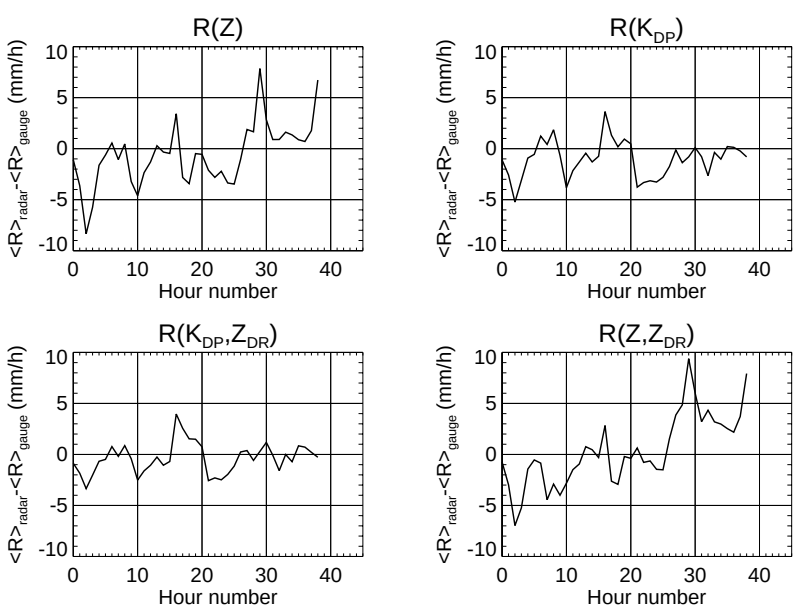

Figure 3. The difference between areal mean rain rates obtained from the radar and gauges for 39 hours of observations during 13 rain events.

5. CONCUSIONS

A comparative analysis of the performance of four radar rainfall estimation algorithms was made. These are conventional R(Z) relation and three polarimetric ones: $R(K_{DP})$, $R(K_{DP}, Z_{DR})$, and $R(Z, Z_{DR})$. The $R(K_{DP}, Z_{DR})$ estimator outperforms others for heavy ($R > 30$ mm h^{-1}) and moderate ($5 < R < 30$ mm h^{-1}) rain, whereas the $R(Z, Z_{DR})$ or R(Z) relations are preferred for light rain ($R < 5$ mm h^{-1}).

Polarimetric method based on the joint use of K_{DP} and Z_{DR} is optimal for addressing two important practical issues: (1) river flooding forecast that involves reliable measurements of areal rainfall accumulations over relatively long periods of time, and (2) urban flash flooding forecasts that implies accurate estimation of very heavy rain over relatively short time intervals.

Even the best non-polarimetric operational radars are prone to the calibration errors that are very difficult to control unless long-term statistics of the radar-gauge comparisons over fixed gauge network is available. These errors adversely affect the performance of the conventional rainfall estimator. In contrast, dual-polarization radar can provide reliable rainfall estimates when reflectivity factor is totally corrupted due to system problems or severe blockage of the radar beam at lower elevation angles.

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