Calibration of Dual-Polarization Radar in the Presence of Partial Beam Blockage

SCOTT E. GIANGRANDE AND ALEXANDER V. RYZHKOV

Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, Norman, Oklahoma

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ABSTRACT

In the presence of partial beam blockage (PBB), weather radar measurements can experience significant bias that directly compromises the accuracy of the hydrologic applications. Techniques for the calibration of the radar reflectivity factor Z and differential reflectivity Z_{DR}, measured with dual-polarization weather radars in the presence of partial beam obstruction, are examined in this paper.

The proposed Z_{DR} calibration technique utilizes radar measurements of Z_{DR} in light rain and dry aggregated snow at unblocked and blocked elevations. This calibration technique was tested for the National Severe Storms Laboratory's (NSSL's) Cimarron radar that suffers from PBB, and a polarimetric prototype of the Weather Surveillance Radar-1988 Doppler (WSR-88D) that does not experience PBB. Results indicate that the Z_{DR} bias that is associated with PBB can be calibrated with an accuracy of 0.2–0.3 dB, provided that the dataset is sufficiently large.

Calibration of Z in the presence of PBB is based on the idea of self-consistency among Z, Z_{DR}, and the specific differential phase K_{DP} in rain. The self-consistency calibration of Z from the Cimarron radar is performed following an area–time integral method. Integration is partitioned into small azimuthal sectors to assess the azimuthal modulation of the Z bias. The suggested technique is validated by direct comparisons of reflectivity factors that are measured by the Cimarron radar and the unobstructed operational WSR-88D radar. It is shown that the azimuthal modulation of Z that is caused by PBB is well captured, and the accuracy of the Z calibration is within 2–3 dB.

1. Introduction

The regular operation of weather radar mandates frequent calibration to ensure accurate measurements. Even modest calibration errors may produce severe deficiencies in the accuracy of radar products, such as rainfall estimation and hydrometeor classification (e.g., Ryzhkov et al. 2005a). In addition to errors introduced by system miscalibration or attenuation in rain, partial blockage of the radar beam (PBB) further exacerbates the problem of accurate radar measurements.

In a recent paper, Maddox et al. (2002) highlight the limits of radar coverage for the operational Next Generation Weather Radar (NEXRAD) Weather Surveillance Radar-1988 Doppler (WSR-88D) network. The study notes that radar coverage below 3 km AGL in the western United States is sparse, with prominent low-level blockage significantly compromising the available radar data. Unobstructed radar data at grazing angles are particularly important during the warm season from a severe weather–warning and forecasting standpoint, and are equally beneficial for many hydrological applications, with emphasis on cold season stratiform events that are typically characterized by low atmospheric melting layers.

Several studies have detailed methods to improve conventional radar-based precipitation estimation quality over complex terrain and at far distances from the radar (e.g., Andrieu et al. 1997; Seo et al. 2000; Dinku et al. 2002; Kucera et al. 2004; Langston and Zhang 2004). In these methods, digital elevation models (DEMs) are used to identify the larger-scale topographical features responsible for a bias in the reflectivity factor Z and resulting radar-rainfall estimates. Details of the correction are contingent on the extent of blockage and may rely on radar data that are obtained at higher tilts or vertical profiles of reflectivity (VPR). Validation of these techniques is often based upon comparisons of corrected radar-rainfall estimates with surface gauge accumulations. However, suggested methodologies have certain limitations. First, the reliability of these methods is questionable when beam

Corresponding author address: Scott E. Giangrande, CIMMS/NSSL, 1313 Halley Circle, Norman, OK 73069.
E-mail: scott.giangrande@noaa.gov

blockage exceeds 60%. The degree of beam blockage depends on atmospheric refractive conditions. This may result in large errors in Z calibration, particularly if anomalous propagation occurs (Bech et al. 2003). In addition to large-scale terrain features, smaller-scale anthropogenic structures (e.g., towers, buildings) and nearby trees that are not accounted for by DEMs cause additional occultation of the radar beam. With the future upgrade of operational radar networks to include polarimetric capabilities, it is also reasonable to examine the impact of PBB on polarimetric variables and investigate alternate techniques for Z retrieval that may benefit from available polarimetric information.

One of the advantages of a dual-polarization radar is its ability to measure the specific differential phase K_{DP}, which is immune to radar system miscalibration, beam blockage, and attenuation in rain. Many studies capitalize on these unique properties of K_{DP} for Z calibration. Ryzhkov et al. (2005a) examined the idea of self-consistency among Z, K_{DP}, and differential reflectivity Z_{DR} (e.g., Goddard et al. 1994; Scarchilli et al. 1996; Vivekanandan et al. 2003) for operational calibration of a prototype of the polarimetric WSR-88D radar that does not experience PBB. The technique, which was originally suggested in Goddard et al. (1994), was modified by introducing an area–time integration approach over a large spatial/temporal domain, and by incorporating multiple consistency relations for the central Oklahoma region. This methodology was tested on a large dataset during the Joint Polarization Experiment (JPOLE) field campaign (Ryzhkov et al. 2005b), and exhibited accuracy to within 1 dB of a local well-calibrated WSR-88D reference radar.

Application of the consistency techniques for Z calibration stipulates unbiased measurements of Z_{DR} and K_{DP}. As opposed to K_{DP}, Z_{DR} can be significantly biased by PBB (Ryzhkov et al. 2002). This bias of Z_{DR} that is caused by blockage is usually manifested by an apparent azimuthal modulation of Z_{DR} in uniform precipitation. Hence, Z_{DR} should be corrected for the effects of PBB prior to calibration of Z if the consistency technique is utilized.

Different methods for absolute Z_{DR} calibration are discussed by Gorgucci et al. (1999), Bringi and Chandrasekar (2001), Hubbert et al. (2003), and Ryzhkov et al. (2005a), among others. They include the measurement of solar radiation at the two orthogonal polarizations and the use of natural scatterers of known polarimetric properties, such as light rain and dry aggregated snow. However, none of these techniques addresses the assessment and correction of the Z_{DR} bias that is caused by PBB.

The outline of this paper is as follows. First, observational evidence of the Z_{DR} bias that is caused by PBB is presented. This evidence includes data collected over a multiyear period from two polarimetric radars at various elevation angles. We will then develop a technique to account for observed biases using the polarimetric properties of Z_{DR} for various weather scatterers at grazing angles. Once an estimate of the Z_{DR} bias has been established, a methodology for the calibration of Z in the presence of PBB will be presented following the operational self-consistency approach presented by Ryzhkov et al. (2005a). Polarimetric radar data provided in this study were collected by the National Oceanic and Atmospheric Administration (NOAA)/National Severe Storms Laboratory (NSSL) 11-cm Cimarron dual-polarization radar that experiences significant beam blockage at the 0.5° elevation angle, and by the polarimetric prototype of the WSR-88D radar (herein KOUN) that does not suffer from blockage at the 0.5° elevation angle.

2. Z_{DR} observations in the presence/absence of a partial beam blockage

a. Blocked radar (Cimarron)

It is often difficult to recognize the adverse effects of beam blockage on the quality of radar measurements if the blockage is not well pronounced. This was precisely the case for the Cimarron polarimetric radar. Although the Cimarron radar sits relatively low, compared to the surrounding terrain (Fig. 1), the impact of PBB on the quality of the dual-polarization measurements was not immediately apparent. The most common manifestations of the problem include persistent radial "valleys" and "ridges" in the Z or Z_{DR} fields in cases of uniform precipitation like stratiform rain and snow. Another indication of this phenomenon is a repetitive negative bias of Z-based rainfall estimates in particular azimuthal sectors. The latter can be revealed only after analysis of long-term statistics of radar–gauge comparisons. The natural spatial variability of the radar variables often obscures blockage-related azimuthal modulations of Z and Z_{DR} over shorter time frames.

The use of meteorological scatterers of known polarimetric properties provides one possible approach to investigate the Z_{DR} bias (e.g., Bringi and Chandrasekar 2001; Hubbert et al. 2003; Ryzhkov et al. 2005a). Light drizzle-type rain and dry aggregate snow are possible natural calibration targets. Nearly spherical drizzle particles should exhibit Z_{DR}s close to zero (in decibels; e.g., Smyth and Illingworth 1998; Bringi and Chandrasekar 2001). However, JPOLE studies indicate that drizzle constitutes only a small portion of light rain with an intensity less than 5 mm h^{-1}, resulting in Z_{DR} values

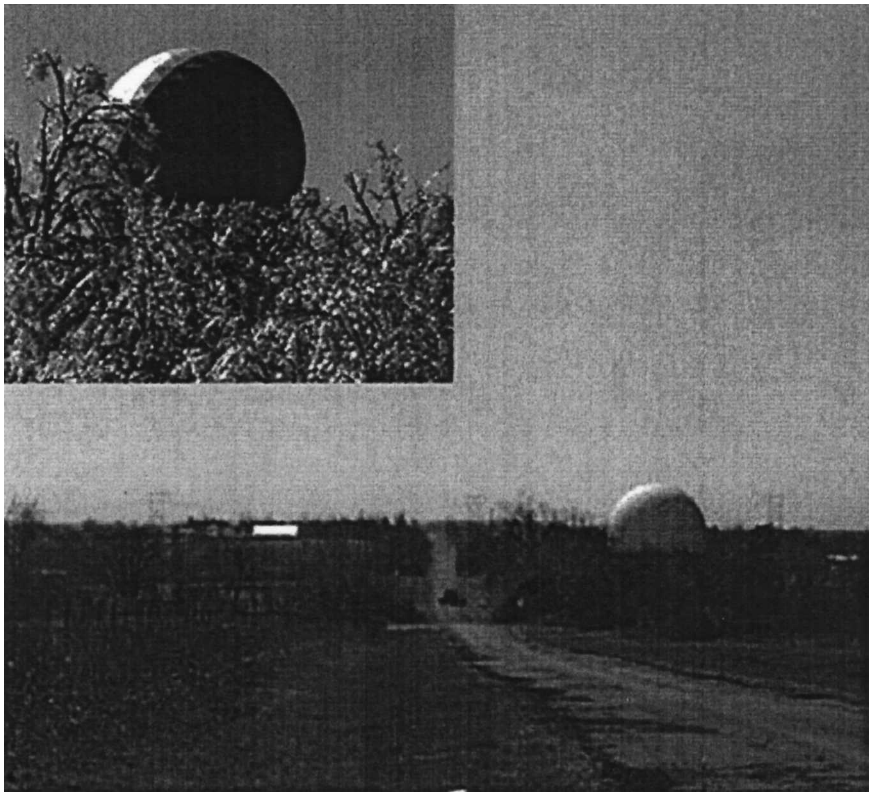

FIG. 1. Image of the Cimarron radar taken during the fall of 2002. The top left corner image shows the radar after an ice storm in Feb 2003.

for light rain that are quite different from zero and are dependent on drop size distributions (Ryzhkov et al. 2005a). Figure 2 illustrates a summary of the mean Z_{DR}–Z dependencies for central Oklahoma that are obtained from multiyear disdrometer data and measurements from the well-calibrated KOUN WSR-88D polarimetric radar that does not experience beam blockage problems. If highly convective events (thick black line) are excluded, the mean Z_{DR} values for light rain with intensities between 1 and 5 mm h^{-1} (Z between 25 and 35 dBZ) commonly vary in the range between 0.4 and 0.8 dB, with median values around 0.5–0.7 dB (which are rather different than zero). Figure 2 represents the Z_{DR}–Z dependencies that are averaged over large number of different rain events with different drop size distributions (DSDs). For given value of Z, the mean Z_{DR} in light rain can vary considerably from storm to storm, depending on the type of DSD. Such variations can be as high as 0.6–0.7 dB (Ryzhkov et al. 2005a). Measurements in dry aggregated snow near the ground usually exhibit a Z_{DR} below 0.3 dB, with a much lower variability than in light rain, provided that wet snow and pristine snow crystals are excluded (Ryzhkov and Zrnic 1998a, 2003).

Because of the high variability of Z_{DR} in light rain, dry snow appears to be a better calibration target for the absolute calibration of Z_{DR} than the rain observed at low antenna elevations. However, the impact of DSDs on Z_{DR} in stratiform rain can be substantially reduced if one examines the difference between Z_{DR} at two adjacent elevations (e.g., 0.5° and 1.5°). Such a difference is usually small in light stratiform rain, provided that both elevations are not blocked. The partial beam blockage at lower elevations can be recognized by an increased value of the Z_{DR} difference.

Identification of the areas of light rain (with rain rates between 1 and 5 mm h^{-1}) requires radar-rainfall estimates that are unbiased by beam blockage. This is guaranteed by the use of K_{DP}, which is immune to PBB.

It is reasonable to expect that, in the absence of PBB, the mean value of Z_{DR} in range gates where $1 <$ $R(K_{DP})$ 5 mm h^{-1} should not depend on the azimuth, provided that the averaging procedure is performed over a sufficiently large volume of data. To confirm this notion, rain rates were computed using the relation (Ryzhkov et al. 2001a)

$$R(K_{DP}) = 42.8|K_{DP}|^{0.802}\,\mathrm{sign}(K_{DP}) \tag{1}$$

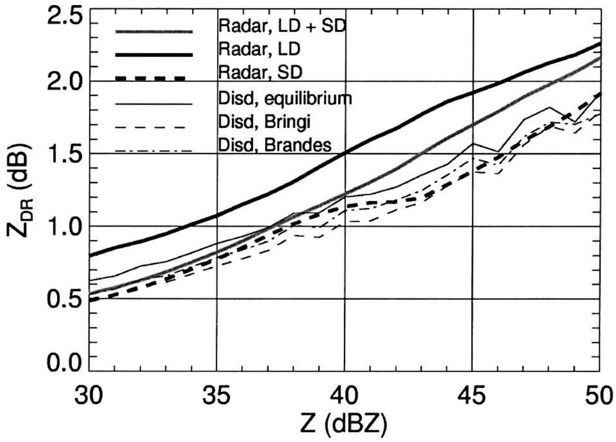

FIG. 2. Mean Z–Z_{DR} dependencies obtained from the radar for different rain regimes, and from the disdrometer using different assumptions about raindrop shapes. "Radar" curves are derived from the KOUN WSR-88D measurements. "Disd" curves are based on the 2D videodisdrometer statistics. "LD" and "SD" curves correspond to rain regimes dominated by large and small drops, respectively. Simulations from disdrometer measurements are made using assumptions about the drop shape following Beard and Chuang (1987), Brandes et al. (2002), and Bringi et al. (2003).

for the Cimarron data collected at the lowest tilt of 0.5°. For several rain events, we identify range gates where $1 < R(K_{DP}) < 5$ mm h^{-1}, and partition these range gates into 1° azimuthal intervals. In light rain ($Z < 40$ dBZ), the estimate of K_{DP} is made using a window of 25 successive gates, which corresponds to a radial resolution of about 6 km. The standard deviation of such a K_{DP} estimate is about 0.05°–0.1° km^{-1} (Ryzhkov and Zrnic 1996). Although the relatively large errors of K_{DP} estimation may incorrectly classify range gates as containing "light rain," the impact of this is minimized when a large number of radials are summed. Because attenuation is nearly linearly proportional to Φ_{DP}, these measurements can also be used to correct Z_{DR} for attenuation in rain (e.g., Bringi et al. 1990). Mean Z_{DR} values for this rain-rate interval are computed and are examined as a function of the azimuth.

Prior to Z_{DR} averaging, range gates with a cross-correlation coefficient ρ_{HV} that is lower than 0.7 are removed. In pure light rain or dry snow, ρ_{HV} usually varies between 0.98 and 0.997, if the dual-polarization radar is well designed. Because of quantization noise in the Cimarron data processor, the measured values of ρ_{HV} are negatively biased, and these high values have never been attained (Ryzhkov and Zrnic 1998b). This should be taken into account when interpreting the Cimarron polarimetric data. Although the absolute values of ρ_{HV} are not reliable, relative changes are still trustworthy. Previous studies indicate that for the Cimarron radar, the 0.7 ρ_{HV} threshold is useful to discriminate between meteorological and nonmeteorological scatterers and to avoid melting-layer contamination (e.g., Ryzhkov and Zrnic 1998b). To further mitigate potential melting-layer contamination, only gates located within 85 km of the radar were examined. Data from the first 12 km have been removed to limit ground clutter contamination. Polarimetric brightband detection that is performed at higher, unobstructed elevation angles (e.g., Giangrande and Ryzhkov 2004) also helps to reduce contamination from mixed-phase hydrometeors.

The results of this analysis for five stratiform rain events are presented in Figs. 3a,b. Each event contains a minimum of three continuous hours of stratiform rainfall observations that include between 13 000 and 21 000 radials of data at the elevation of 0.5°. It is clear that averaged values of Z_{DR} at the 0.5° elevation exhibit a repetitive azimuthal dependency. In addition, the magnitude of Z_{DR} for nearly all azimuths is much lower than the expected 0.4–0.8 dB in Fig. 2. The composite curve in Fig. 3b shows that the standard deviation of the Z_{DR} bias estimates for each azimuth is about 0.2 dB.

Similar dependencies of Z_{DR} have been obtained for a number of snow events (Figs. 4a,b). Each of the seven events contained a minimum of 2.5 continuous hours of snowfall data. For several of these cases, the number of azimuths exceeded 12 000 individual radials per event; however, individual radial counts on the order of 5000 were more typical as a result of changes in the radar scanning strategy. In fact, the results in Fig. 4 exhibit a striking resemblance with the azimuthal modulation that is observed for light rain events, with Z_{DR} values that are about 0.3 dB lower, as expected. The composite curve (Fig. 4b) once again shows that the standard deviation of the difference between individual curves is about 0.2 dB.

The hypothesis that PBB is responsible for the observed azimuthal modulation was confirmed by the fact that a pronounced azimuthal modulation was not revealed at the next available, and mostly unblocked, elevation angle of 1.5°. The difference of Z_{DR} that is measured at the unblocked (1.5°) and blocked (0.5°) elevation angles is shown in Figs. 5a,b. Unfortunately, data at 1.5° were not available for all of the events illustrated in Figs. 3 and 4. For the cases shown in Fig. 5, however, the observed difference between the elevation angles remains relatively stable for several years. The mean standard deviation of the Z_{DR} difference at each azimuth for these events is 0.12 dB. Analysis of reflectivity data during this period shows that the Z difference between 1.5° and 0.5° is typically within 3

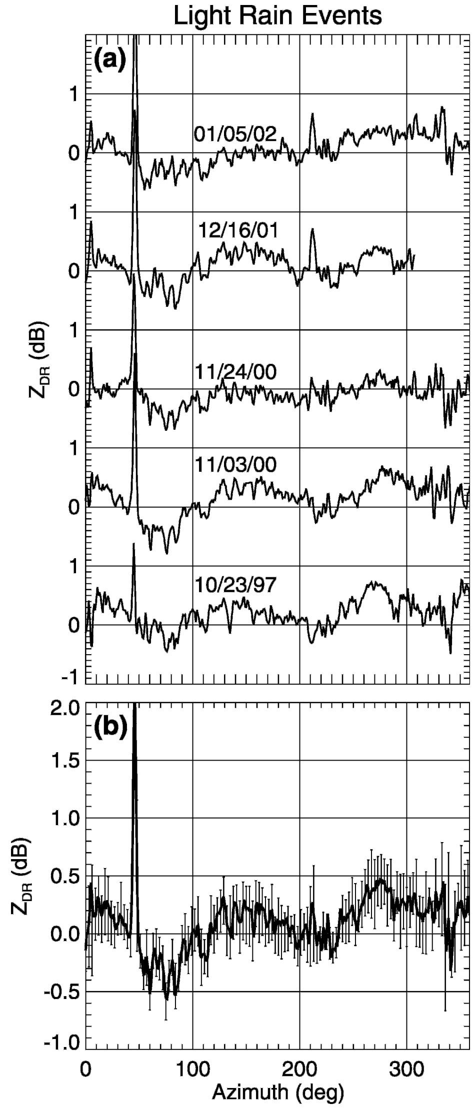

FIG. 3. (a) Azimuthal dependencies of Z_{DR} measured by the Cimarron radar at the 0.5° elevation angle for five rain events; (b) mean azimuthal dependence for these events. The error bars indicate the range of Z_{DR} variations for all cases.

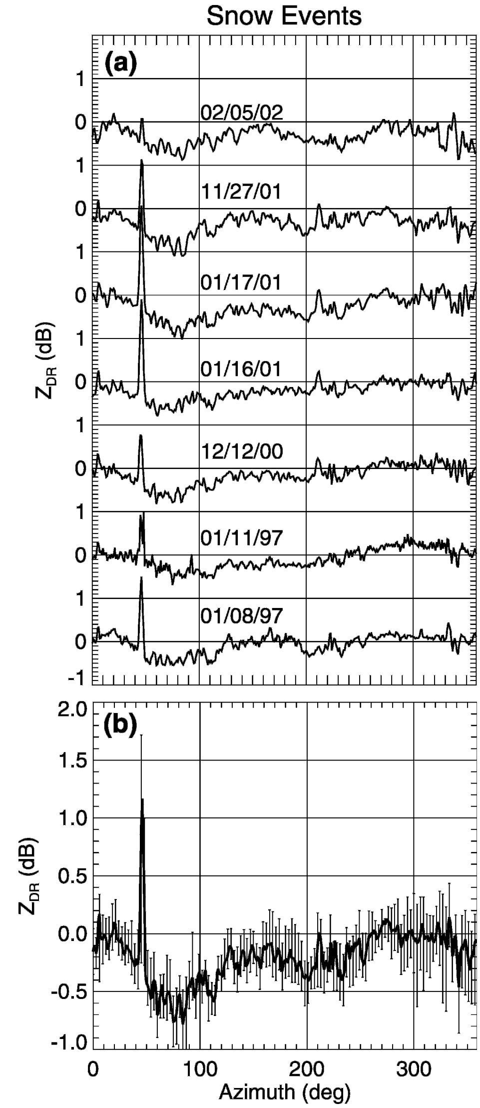

FIG. 4. Same as Fig. 3, but for seven snow events.

dB. This suggests that the radar blockage is usually less than 50% in most directions.

As Fig. 5 shows, the Z_{DR} bias resulting from PBB is unacceptably high, and approaches 0.8 dB in certain azimuthal sectors. This magnitude of the bias is particularly noteworthy for a radar located in the Great Plains, without rugged or mountainous terrain in close proximity. To estimate rainfall with an acceptable accuracy, the required accuracy of Z_{DR} measurements should be 0.2 dB for moderate-to-heavy rainfall, and 0.1 dB for light rain (Ryzhkov et al. 2005a). Therefore, the correction for possible PBB must be performed before the polarimetric rainfall estimation is made.

The origin of the Z_{DR} bias that is associated with PBB may stem from a variety of sources. First, the antenna beams at the horizontal (*H*) and vertical (*V*) polarizations are not perfectly identical, and, therefore, may be obstructed differently by the same obstacle. A second possible cause is multipath propagation with different characteristics for *H* and *V* radio waves. Finally, semitransparent obstacles (like nearby trees) might have different degrees of transparency for *H* and *V* radiation, similar to the polarimetric grids. Note that the spike at Az = 45° in Fig. 4a almost disappeared on 5 February 2002 following an extreme ice storm that was responsible for breaking several large trees in the vicinity of the radar. Minor seasonal variations might be potentially attributed to the presence/absence of foliage on nearby trees.

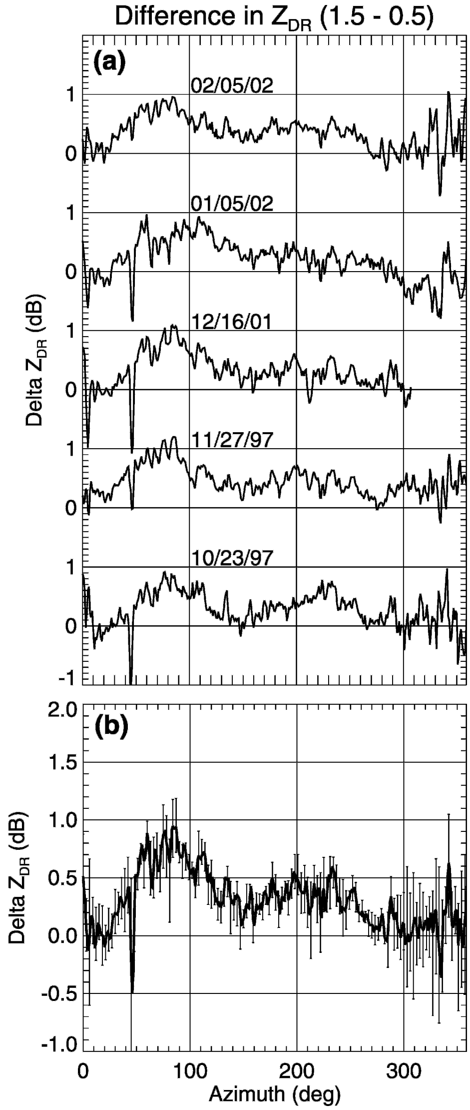

FIG. 5. (a) Difference between the mean azimuthal dependencies of Z_{DR} at the 1.5° and 0.5° elevation angles for five events; (b) mean azimuthal dependence for all five events. The error bars indicate the range of variation in the difference field.

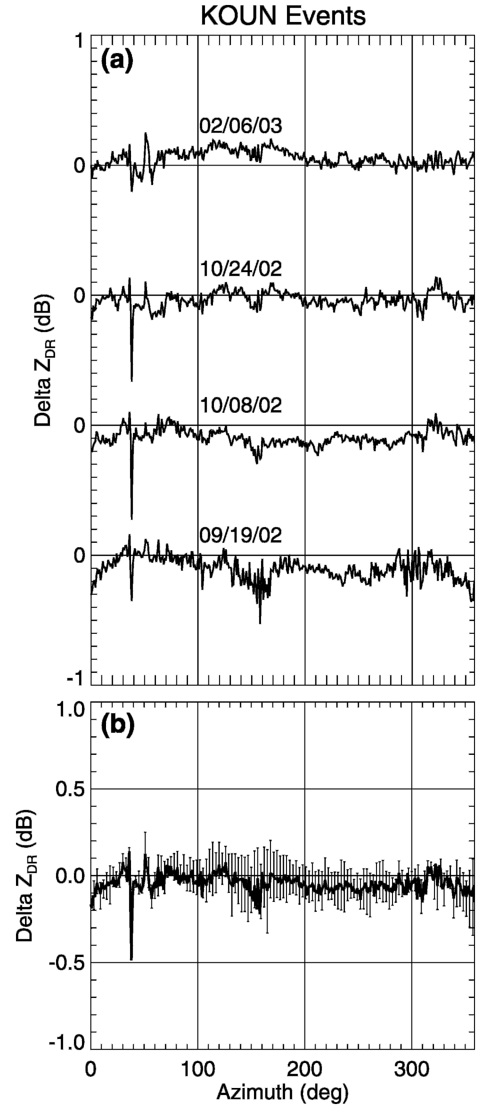

FIG. 6. Same as Fig. 5, but for four events observed by the KOUN radar.

b. Unblocked radar (KOUN WSR-88D)

The same methodology was applied to the KOUN WSR-88D polarimetric radar data, which were presumed to be much less affected by PBB at the 0.5° elevation angle. A summary of four events (rain on 19 September 2002, 8 October 2002, and 24 October 2002, and snowfall on 6 February 2003) is presented in Figs. 6a,b, where the difference between Z_{DR} at the 1.5° and 0.5° elevation angles is displayed as a function of azimuth (four individual curves and one composite curve). Regions of light rain were identified using the classification algorithm described by Schuur et al. (2003). As with the Cimarron data, only gates in which $1 < R(K_{DP}) < 5$ mm h^{-1} were examined.

The difference in the mean Z_{DR} at the two elevations for the light rain events is particularly small and does not exhibit a pronounced azimuthal dependence. The mean value does not differ from zero by more than 0.1–0.2 dB. The only exceptions are the azimuthal directions of 36° and 157°, at which a tower of another WSR-88D radar and large University of Oklahoma buildings are located. The mean standard deviation of the Z_{DR} difference at each azimuth is 0.06 dB. This result confirms that the KOUN radar does not experience a noticeable bias resulting from PBB, except for a few isolated directions where high towers or buildings are located.

Out of the four snowfall events that are observed during the JPOLE project, the 6 February 2003 event was selected for analysis because of its large spatial extension and uniformity. Frequent ground observations were also available during this case, which confirm that the snow consisted primarily of large dry aggregates. Similar to the rain events, the difference in Z_{DR} between the lowest two elevation angles is within 0.1 dB.

3. Methodology for Z_{DR} calibration in the presence of PBB

The suggested calibration of Z_{DR} in the presence of PBB can be formulated as follows.

1) Absolute calibration of Z_{DR} has to be performed at high (unobstructed) elevation angles, as described by Ryzhkov et al. (2005a). This calibration implies the measurements of solar radiation at the two orthogonal channels and/or the use of polarimetric properties of dry aggregated snow above the melting layer. These techniques demonstrate an ability to calibrate Z_{DR} with an accuracy of 0.2 dB, which is sufficient for most hydrological applications.
2) Regions of light rain should be identified using a polarimetric classification algorithm (Schuur et al. 2003) and K_{DP} measurements that are immune to PBB. The algorithm described in Schuur et al. (2003) is based on the fuzzy-logic approach and utilizes Z, Z_{DR}, ρ_{HV}, and texture parameters of Z and Φ_{DP}, standard deviation SD(Z), and SD(Φ_{DP}). The cross-correlation coefficient ρ_{HV} is not affected by PBB, provided that the signal-to-noise ratio is sufficiently high. Because the distinction between the rain and nonrain echo (e.g., bright band, ground clutter, biological scatterers) is mostly affected by ρ_{HV}, SD(Z), and SD(Φ_{DP}), and to a lesser extent by Z and Z_{DR}, the moderate biases of Z and Z_{DR} resulting from PBB do not dramatically impact the results of such a rain versus nonrain classification. Zero weights can be assigned to Z and Z_{DR} measurements if very large biases are expected.

   Classification should be performed for all of the elevation angles that are examined. The selection of range gates with $1 < R(K_{DP}) < 5$ mm h^{-1} provides further confidence that only the data that are associated with light rain are chosen for subsequent averaging of Z_{DR}. An alternate option is to use more reliable and unbiased Z and Z_{DR} data at higher elevation angles to identify regions of light rain. This option implies that light rain is present at both elevations.
3) In the case of snow, one has to ensure that the snow type is suitable for Z_{DR} calibration, that is, it has an intrinsic Z_{DR} of a few tenths of a decibel. Such Z_{DR} is usually observed for dry aggregated snow (Ryzhkov and Zrnic 1998a, 2003). Classification of this type of snow is more challenging than the classification of light rain, and is often contingent on additional observational data (surface temperatures, soundings, etc.). Crystallized snow is characterized by high values of Z_{DR} and K_{DP}, whereas wet aggregated snow is associated with low ρ_{HV} combined with a high Z_{DR} and moderate K_{DP} (similar to the bright band).
4) Once appropriate scatterers (light rain or dry snow aggregates) are identified, the mean value of Z_{DR} corresponding to these scatterers should be computed as a function of the azimuth at the potentially blocked and unblocked elevations. The dataset should be large enough to ensure acceptable statistical error in the mean Z_{DR} value for every azimuthal interval defined by radar resolution in the azimuth. In this study, 1–4 h of data were used for such estimations. Further investigations are required to evaluate more objectively the amount of data that are needed.
5) It is very likely that in the case of snow the intrinsic Z_{DR} might exhibit a pronounced increase with height (Ryzhkov and Zrnic 1998a). If this happens and the mean Z_{DR} at the lowest unblocked elevation angle exceeds 0.3 dB, then it is recommended that only Z_{DR} data from the lowest (blocked) elevation be used.

For each azimuth, the Z_{DR} bias that is caused by PBB is determined as

$$\Delta Z_{DR} = [Z_{DR}(\text{blocked})] - [Z_{DR}(\text{unblocked})] \quad (2)$$

in the case of rain and snow ⟨if [Z_{DR}(unblocked)] in snow is less than 0.3 dB⟩, and

$$\Delta Z_{DR} = [Z_{DR}(\text{blocked})] - 0.2 \text{ dB}, \quad (3)$$

in the case of snow if [Z_{DR}(unblocked)] is larger than 0.3 dB. It is assumed in (3) that the average intrinsic value of Z_{DR} in snow is equal to 0.2 dB.

4. Z calibration in the presence of partial beam blockage

After Z_{DR} is calibrated using the technique described in the previous section, the principle of self-consistency among Z, Z_{DR}, and K_{DP} in the rain medium can be applied as a means to estimate Z bias that is expected to change with azimuth as a function of PBB.

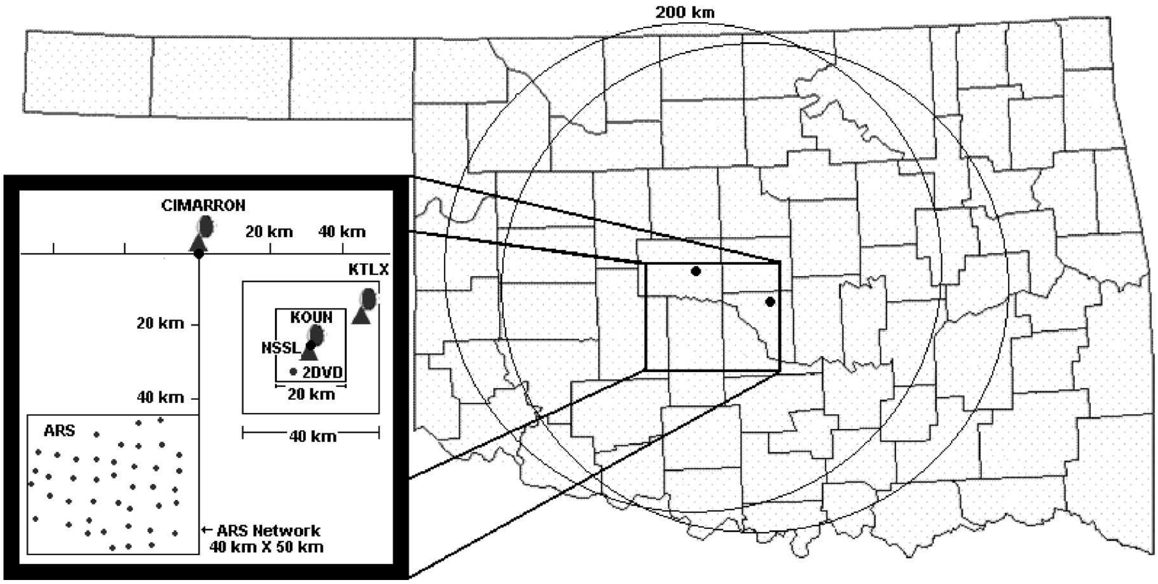

FIG. 7. Location of radars and the ARS network rain gauges in central Oklahoma.

a. Self-consistency Z calibration approach in the presence of PBB

To investigate the Z bias that is caused by PBB for the Cimarron radar, this study adopts a modified version of the self-consistency approach offered by Ryzhkov et al. (2005a). According to the consistency principle, the radar reflectivity factor in rain can be roughly estimated from Z_{DR} and K_{DP}, using the relation

$$Z = a + b\log(K_{DP}) + cZ_{DR}, \qquad (4)$$

where a, b, and c are constant coefficients (Z is expressed in dBZ, K_{DP} is in deg km^{-1}, and Z_{DR} is in dB). Then, the area–time integrals of the measured K_{DP} and the K_{DP}, estimated from Z and Z_{DR} using (4), are matched by adjusting Z. This type of Z adjustment has to be performed separately for different azimuthal intervals. Because the relation (4) is valid for rain only, all nonrain echoes should be identified and filtered out prior to the application of the consistency technique.

The coefficients in (4) are usually derived from large statistics of disdrometer measurements or direct radar observations in rain. A large number of the consistency relations can be found in the literature. Comparative analyses of the performance of different consistency formulas have been performed by Ryzhkov et al. (2005a) on the extensive polarimetric radar dataset obtained during JPOLE. Ryzhkov et al. (2005a) found that additional improvement could be achieved if more than one consistency relation was used. The study recommends the following two relations that work best for central Oklahoma rain events:

$$Z = 46.0 + 9.55\log(K_{DP}) + 1.68\,Z_{DR}, \qquad (5)$$

and

$$Z = 44.0 + 12.2\log(K_{DP}) + 2.32\,Z_{DR}. \qquad (6)$$

The need to use more than one consistency relation is dictated by a very high diversity of rain regimes and associated DSDs in Oklahoma. There is no unique consistency formula that "matches" all rain types. Equation (5) works better in the cases of DSDs that are dominated by small drops, and Eq. (6) is preferable for DSDs that are characterized by a prevalence of large drops with a relative deficit of small drops. Two estimates of the Z bias are derived from (5) and (6), with only one accepted for a particular rain event, using criteria formulated in Ryzhkov et al. (2005a).

In this study, the Z biases that are caused by PBB are examined in a limited azimuthal sector between 180° and 220° that contains the Agricultural Research Service (ARS) Micronetwork gauges (Fig. 7). The ARS area was also used for independent verification of the Cimarron radar calibration using the data from the operational KTLX WSR-88D radar that is located 20 km off of the Cimarron radar.

Consistency relations (5) and (6) were applied separately for 5° azimuthal sectors within the 180°–220° interval to compute two sets of estimates of the Z bias as a function of the azimuth. The 5° increment was assumed to be adequate to resolve most details of the expected azimuthal modulation of the Z bias that is attributed to PBB for several reasons. Although Z_{DR} biases were obtained for 1° increments, mean azimuthal dependencies (e.g., Fig. 3) indicate that resolving most modest changes in the Z_{DR} bias (excluding the larger towers) does not require such a high level of detail. In addition, because the consistency technique utilizes area–time integrals of K_{DP}, an increase in the sector size should decrease the collection time for a valid calibration to be performed.

Alternate estimates of the bias in the Cimarron reflectivity factor were obtained via the direct comparison of reflectivity factors measured by the Cimarron and KTLX radars. Direct comparison of the instantaneous Z fields from the Cimarron and WSR-88D radars is not the best way to quantify the bias that is a function of azimuth with respect to the Cimarron radar. Instead, we compare point estimates of 1-h rainfall accumulation for each of the 42 rain gages constituting the ARS network from both radars, using a conventional WSR-88D $R(Z)$ algorithm, and determine how the difference between the two is projected into a difference in Z.

b. *Results of Z calibration*

Figure 8 represents a summary of the Z bias estimates obtained from the consistency method (solid lines) and direct KTLX–Cimarron comparisons (diamonds and dashed lines, respectively) for five widespread rain events. Each event contains a minimum of two consecutive hours of hourly KTLX–Cimarron rainfall comparisons, and a minimum of 3 h of accumulated radar data for the consistency-based calibration. Every diamond in Fig. 8 indicates the result of the KTLX–Cimarron comparison obtained from 1 h of observations for a particular rain gauge. The dashed lines represent the mean azimuthal dependencies of the Z bias obtained from the direct KTLX–Cimarron comparisons.

Similar to Z_{DR}, the bias of Z exhibits a well-pronounced azimuthal modulation, even within a relatively narrow sector of less than 40°. The azimuthal dependencies of the bias that are obtained from the consistency method and direct KTLX–Cimarron comparisons show good agreement in four out of five events (except for the event on 23 October 1997). In the case on 25 October 2000, the two estimates of the Z offset show very similar azimuthal dependencies, but the absolute values of the biases are about 3 dB off for all of the azimuths examined.

A general increase in the magnitude of the negative Z bias during the 4-yr period is well captured by both methods. Note that such degradation is mostly related to the system problems with the Cimarron radar. As mentioned previously, partial beam blockage is responsible for no more than 3 dB of the azimuthally modulated offset.

It is very difficult to quantify the accuracy of the

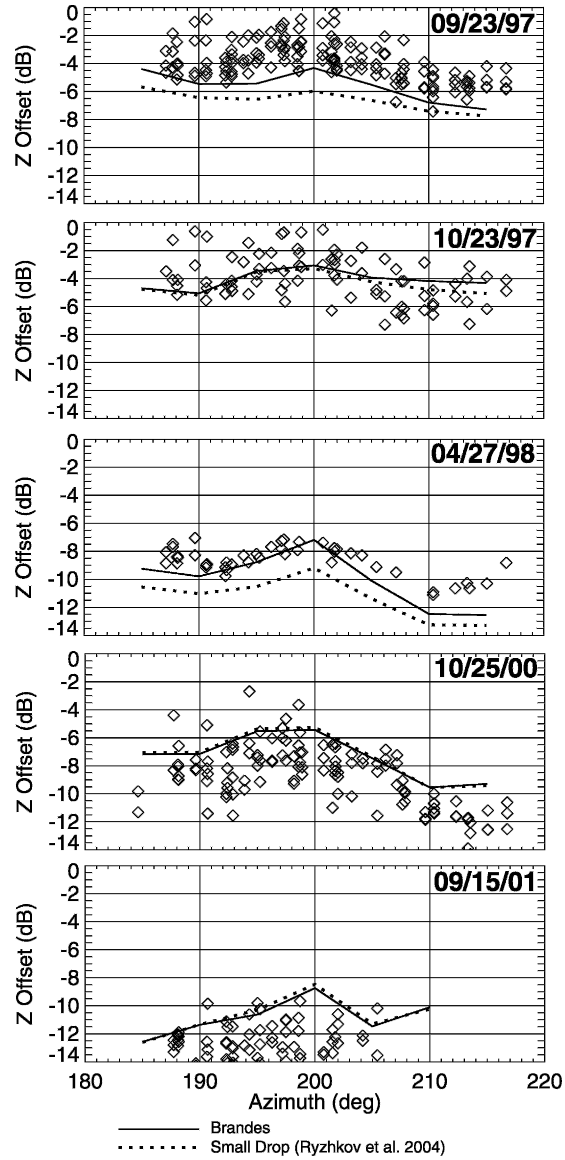

FIG. 8. Bias of Z measured by the Cimarron radar as a function of the azimuth for five rain events. Diamonds and dashed lines indicate results of direct comparisons of Z from the Cimarron and WSR-88D data. The solid curves represent results of consistency-based retrievals.

suggested technique for Z calibration using direct comparisons of reflectivity factors from the KTLX and Cimarron radars. This is because the direct method shows significant uncertainty. There are also indications that the operational KTLX radar could be noticeably miscalibrated itself. The comparison of rainfall estimates from gauges and both radars, using conventional and polarimetric rainfall algorithms, shows that reflectivity from the KTLX radar was likely negatively biased prior to the fall of 2000 and was positively biased thereafter (Ryzhkov et al. 2001b).

The rms difference between the two estimates of the Z bias that is obtained from the consistency technique and direct comparisons of reflectivity factor measured by the KTLX and Cimarron radar is about 2.4 dB for all of the five cases combined.

5. Summary

Partial beam blockage (PBB) causes biases in the radar reflectivity factor Z and differential reflectivity Z_{DR}. Such biases manifest themselves as azimuthal modulations of Z and Z_{DR} in spatially uniform precipitation, such as stratiform rain and snow. The biases may stem from larger terrain features (e.g., hills and mountains) or smaller obstructions in close proximity of the radar (towers, tall buildings, trees, etc.)

To recognize PBB, it is recommended that the azimuthal dependences of the mean Z_{DR} are examined for light rain, with an intensity between 1 and 5 mm h^{-1}, or dry aggregated snow at several elevation angles, including potentially blocked and unblocked elevations. Identification of the areas containing light rain should be performed using polarimetric classification of radar echoes and measurements of specific differential phase K_{DP} that is not affected by PBB. Dry aggregated snow should be distinguished from other snow types, such as pristine ice crystals and wet aggregates, that are not efficient for the recognition of PBB.

Regular observations with the Cimarron polarimetric radar reveal azimuthal modulations of Z_{DR} at the elevations of 0.5° with depths up to 0.8 dB. No such modulation was observed for the polarimetric prototype of the WSR-88D radar. The Z_{DR} bias that is caused by PBB is estimated as a difference between the mean values of Z_{DR} measured in light rain or dry aggregated snow at the lowest unblocked and blocked elevations. Such a difference can be estimated with an accuracy of about 0.1 dB, provided that the dataset is sufficiently large. Absolute calibration of Z_{DR} at higher, unblocked elevations can be performed using the methods described in the literature (e.g., Gorgucci et al. 1999; Bringi and Chandrasekar 2001; Hubbert et al. 2003; Ryzhkov et al. 2005a).

Once Z_{DR} is corrected for effects of PBB, a self-consistency approach capitalizing on the interdependency of Z, Z_{DR}, and K_{DP} in rain can be applied to calibrate Z at every azimuthal interval. The consistency technique that was originally proposed by Goddard et al. (1994) and Scarchilli et al. (1996), and was recently modified by Ryzhkov et al. (2005a), has been tested for several widespread rain events that are observed with the Cimarron radar.

The Z bias estimates that are obtained from the consistency approach in the presence of PBB have been validated using direct comparisons of radar reflectivity measured by the Cimarron radar and the unobstructed operational KTLX WSR-88D radar. The two techniques exhibit similar azimuthal dependencies of the Z bias resulting from PBB. The rms difference between the biases of Z that are obtained from the two methods is about 2.4 dB for all of the five cases examined.

Our technique does not require using digital elevation maps of terrain and does not rely on any assumptions about refractive conditions in the atmosphere. Although in the case of the Cimarron radar the occultation of the radar beam at an elevation of 0.5° was relatively moderate (generally less than 50%), we expect that the proposed method is applicable in the presence of more severe blockage.

The suggested methodology might be helpful to improve the quality of radar data collected at potentially blocked low antenna elevations that are beneficial to perform rainfall measurements that are less affected by brightband contamination, to detect regions of convection initiation associated with surface-based gust fronts, and for more efficient polarimetric tornado detection (Ryzhkov et al. 2005c).

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