P5.15 CALIBRATION OF THE POLARIMETRIC NEXRAD RADAR USING METEOROLOGICAL SIGNALS

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1. Introduction

Regular operation of weather radar mandates frequent calibration to ensure accurate measurements. Even modest calibration errors in reflectivity factor Z and differential reflectivity Z_{DR} may produce severe deficiencies in the quality of radar products such as rainfall estimates and hydrometeor classes. Radar users, including the Federal Aviation Administration (FAA), rely on high quality weather radar data to ensure efficient operations.

Techniques for absolute calibration of Z and Z_{DR} measured with dual-polarization weather radars are examined in this paper. The idea of polarimetric self-consistency in the rain medium is tested for Z calibration (e.g., Goddard et. al 1994, Scarchilli et al. 1996, Vivekanandan et al. 2003) and the polarimetric properties of natural weather scatterers are used for Z_{DR} calibration (e.g., Gorgucci et al. 1999, Bringi and Chandrasekar 2001). The Z calibration procedure is implemented in real-time and tested using a large dataset collected during the Joint Polarization Experiment (JPOLE). This calibration routine operates continuously for the standard VCP during data acquisition and processing.

2. Calibration of Z and Z_{DR}

a. *Absolute calibration of Z based on polarimetric self-consistency*

Radar reflectivity factor in rain can be roughly estimated from Z_{DR} and K_{DP} using the relation

$$Z = a + b \log(K_{DP}) + c Z_{DR}, \quad (1)$$

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. The coefficients in (1) are usually derived from statistics of large sets of disdrometer measurements or direct radar observations using well-calibrated radar. A large number of consistency relations can be found in the literature (e.g., Vivekanandan et al. 2003). Since K_{DP} can be quite noisy, especially in light rain, Goddard et al. (1994) recommend expressing K_{DP} as a function of Z and Z_{DR} and examining its integral, the total differential phase

$$\Phi_{DP}^{est}(R) = 2\int_0^R K_{DP}(Z, Z_{DR})\, dr \cdot \quad (2)$$

The radial profile of the measured differential phase Φ_{DP} is then compared to the radial profile of estimated differential phase Φ_{DP}^{est}. If the radar is perfectly calibrated then the two radial profiles should be very close to each other in the rain medium. The mismatch between these two profiles indicates possible calibration error of Z. This error can be determined as an adjustment to Z that is required to match the two profiles of differential phase.

Working with the JPOLE polarimetric data, we found that although the idea of the Z calibration based on self-consistency is quite viable, there are serious methodological problems with practical implementation of this idea in an operational environment. First, there are several consistency relations available in the literature obtained with different assumptions about drop size distribution (DSD) and raindrop shapes. These relations produce noticeably different results in estimation of the Z bias. The discrepancy between relationships might point to the fact that the consistency technique is much more affected by uncertainty in DSDs and raindrop shapes than was previously thought. Second, there is a lack of an explicitly described procedure for “matching” the measured and estimated radial profiles of Φ_{DP}. In addition, this method works only if differential phase is sufficiently large, which limits its utility for many light-to-moderate rain events.

We suggest a different procedure for absolute calibration of Z using self-consistency principles. Instead of examining individual radial profiles of measured and estimated differential phases, area-time integrals of measured K_{DP} and K_{DP} estimated from (1) are matched by adjusting Z (Ryzhkov et al. 2004). By integrating specific differential phase over a large area-time domain we substantially reduce the inherent noisiness in point estimates of K_{DP} and make light rain events (producing very low Φ_{DP}) suitable for polarimetric calibration of Z. This integration was done for individual one-hour polarimetric data sets obtained in the 50 x 40 km Agricultural Research Service (ARS) Micronet test area in central Oklahoma.

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Since the relation (1) is only valid for rain, all non-rain echoes should be identified and filtered out prior to application of this consistency technique. This can be accomplished through the use of a simple fuzzy logic classification algorithm that distinguishes rain from rain/hail, ground clutter, and biological scatterers. All Z bias estimates must also satisfy several quality control conditions before they may be accepted. These measures include a minimum threshold for the K_{DP} integration to ensure sufficient rain in the domain to reduce statistical errors. Also, an assessment is made to establish how representative the given consistency relation is for the current precipitation regime (i.e., does the observed DSD match well the "average" DSD that is assumed for a particular consistency formula).

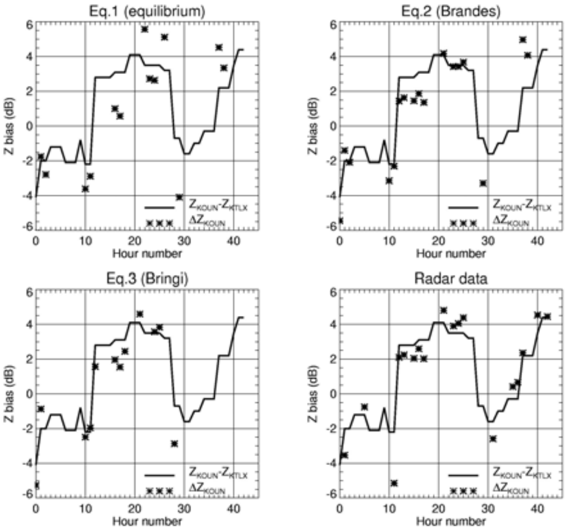

Fig. 1. The bias of reflectivity measurements by the KOUN WSR-88D radar as a function of the hour of observations ranked in chronological order. $Z_{KOUN} - Z_{KTLX}$ is the difference between reflectivities measured by the KOUN and KTLX WSR-88D radars. ΔZ_{KOUN} from the DSD-based and radar data based (bottom right panel) consistency relations are in asterisks.

Figure 1 illustrates results of the KOUN calibration from direct comparisons of the difference between KOUN radar and the local KTLX WSR-88D reflectivities (solid lines) and from polarimetric consistency technique provided the given consistency relation satisfied quality control. For direct radar comparisons, we estimated hourly rain totals over the ARS area using a conventional R(Z) algorithm from simultaneous KOUN and KTLX reflectivity data at the 0.5° elevation. We then calculated the needed adjustment to the Z measurements from KOUN to match these two estimates. Figure 1 presents polarimetric estimates of Z bias from three consistency relations derived from the existing statistics of DSD measurements in central Oklahoma (Schuur et al. 2001) using raindrop shapes specified by Beard and Chuang (equilibrium) (1987), Brandes et al. (2002), and Bringi et al. (2003), respectively. The figure displays the results of consistency calibrations (asterics) for the hours that pass quality control. The agreement between estimates of Z bias from direct radar-to-radar comparisons ($Z_{KOUN} - Z_{KTLX}$) and from polarimetric consistency relations (ΔZ_{KOUN}) is noticeably improved once this quality control is performed. Reduction of the RMS difference between the two estimates is from 1.81 dB to 1.43 dB for the relation using Brandes et al. (2002) drop shape and from 1.93 dB to 1.36 dB for the relation using Bringi et al. (2003) drop shape following these quality control measures.

Additional improvement can be achieved if more than one consistency relation is used. Using KOUN radar data collected over the ARS network, two consistency relations were derived that are matched with rain regimes dominated by large and small drops

$$Z = 44.0 + 12.2 \log(K_{DP}) + 2.32 Z_{DR} \quad (3)$$

for large drop regimes ("LD") and

$$Z = 46.0 + 9.59 \log(K_{DP}) + 1.68 Z_{DR} \quad (4)$$

for small drop regimes ("SD"). Studies from JPOLE suggest that the difference between the "LD" and "SD" regimes is well pronounced.

Consistency relations (3) and (4) were used to compute two estimates of the Z bias for each hour of observation (Fig. 1, bottom right). If both estimates passed quality control, the one that performed best in the quality control was accepted. The $Z_{KOUN} - Z_{KTLX}$ and ΔZ_{KOUN} estimates agree better than in the other panels in Fig. 1 with only one obvious outlier at hour = 11. The corresponding RMS difference between the two estimates is 1.04 dB (0.77 dB if the outlier at hour = 11 is excluded). Thus, application of two consistency relations has resulted in an increase of valid hourly estimates and improved accuracy.

b. *Absolute calibration of Z_{DR} using natural weather scatterers*

Accurate Z_{DR} calibration is crucial for successful applications of dual-polarization radar. This is also important for implementation of the consistency technique, which assumes unbiased Z_{DR} measurements. Existing methods for Z_{DR} calibration use polarimetric properties of solar radiation (e.g., Melnikov et al. 2003) or natural weather targets (e.g., Gorgucci et al. 1999, Bringi and Chandrasekar 2001). The latter

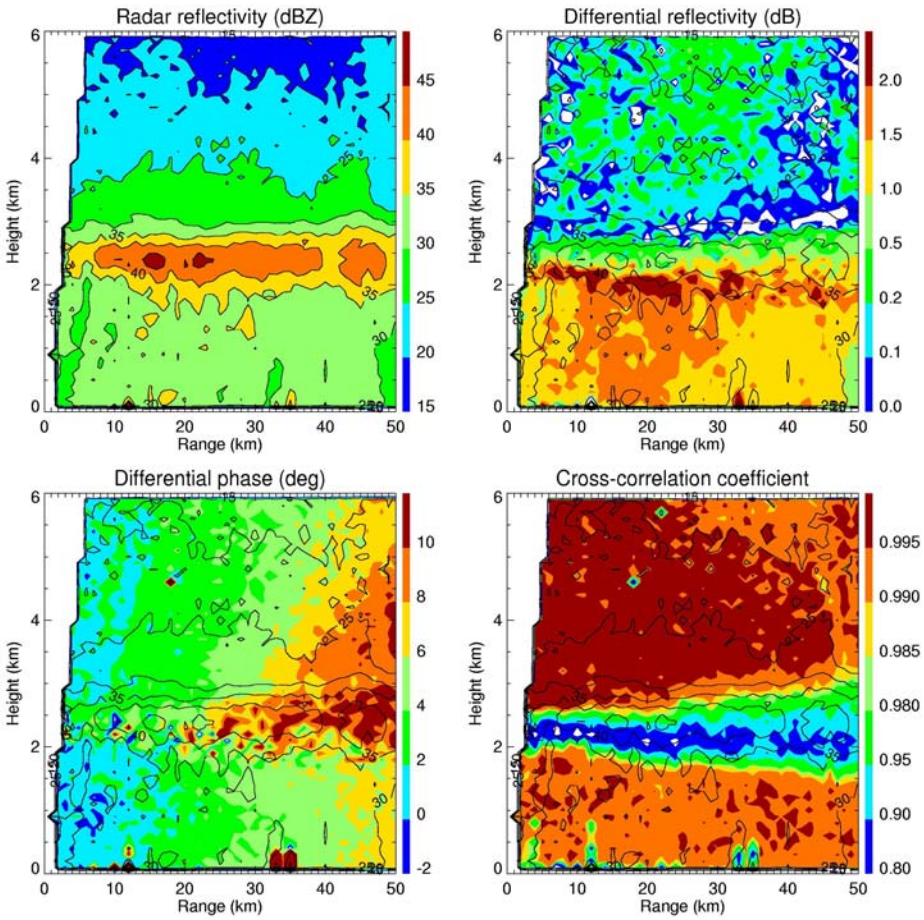

Fig. 2 Composite RHI plot of Z, Z_{DR}, Φ_{DP}, and ρ_{HV} measured with the KOUN WSR-88D radar on 7 April 2002.

involves vertical sounding of rain. The problem with the operational WSR-88D radars is that vertical sounding for Z_{DR} calibration cannot be directly implemented with WSR-88D radar. This is because the antenna has a 60º elevation limit determined by the structural configuration of the antenna's pedestal.

Atmospheric scatterers with low variability of intrinsic Z_{DR} at high elevation angles can serve as natural reflectors for Z_{DR} calibration. One possible calibration medium is dry aggregated snow known for its small intrinsic Z_{DR} due to very low density. Our analysis of several snow cases during JPOLE confirms the previous findings by Ryzhkov and Zrnic (1998) that mean values of Z_{DR} (i.e., averaged over sufficiently large spatial / temporal interval) in dry aggregated snow usually do not exceed 0.25 dB. The variability of Z_{DR} at the 60° elevation will be less than 0.1 dB for this type of scatterers following theoretical considerations from Bringi and Chandrasekar (2001) and Ryzhkov et al. (2004).

Dry aggregated snow should be carefully separated from wet aggregated snow and dry crystallized snow, which are characterized by much higher and more variable Z_{DR} (Ryzhkov and Zrnic 1998). For most climatic regions, dry aggregated snowflakes are present above the melting layer in stratiform clouds. Numerous polarimetric radar measurements show that Z_{DR} dips almost to zero slightly above the bright band maximum of Z and 0°C level and usually remains close to zero in the 1 – 2 km layer above (Ikeda and Brandes 2003), where dry aggregated snow is most likely. An example of such vertical dependence is illustrated in Fig. 2 where a composite RHI plot of Z, Z_{DR}, Φ_{DP}, and ρ_{HV} measured with the KOUN WSR-88D radar on 7 April 2002 is presented. As Fig. 2 shows, Z_{DR} in snow above the bright band remains within 0.1 – 0.2 dB, even for elevation angles much lower than 60°. Notable is a sharp contrast between high values of Z_{DR} in light rain below the bright band and very low values of Z_{DR} in dry aggregated snow above the bright band. Hence, absolute calibration of Z_{DR} should be possible using natural scatterers at lower than 60° elevation angles, provided that the bright-band polarimetric signatures are well defined, differential attenuation is negligible, and SNRs in the H and V channels are sufficiently large.

3. Calibration of Z_{DR} and Z in the presence of blockage

a. Z_{DR} calibration in the presence of partial beam blockage (PBB)

It is often difficult to recognize the adverse effects of partial beam blockage on the quality of radar measurements if this blockage is not well pronounced. This was precisely the case for the NSSL Cimarron polarimetric radar. 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 (e.g., Ryzhkov et al. 2002). To assess Z_{DR} biases at low elevation angles, we suggest natural weather scatterers such as light rain and dry aggregated snow.

Analysis of JPOLE data shows that light rain is not an optimal medium for absolute calibration despite the expectation of Z_{DR} close to zero in light rain and drizzle (in dB scale, e.g., Bringi and Chandrasekar 2001 sec 7.4.2). Spherical drizzle constitutes only a small portion of light rain with intensity less than 5 mm h^{-1}, resulting in Z_{DR} values for light rain quite different from zero and dependent on DSD. However, by identifying regions with light rain (rain rates between 1 and 5 mm h^{-1}) or dry aggregated snow, one should be able to calibrate Z_{DR} with accuracy to a few tenths of a dB. Such identification requires radar rainfall estimates unbiased by PBB. This is guaranteed by the use of K_{DP}. It is also assumed that in the absence of PBB and at close distance to the radar, the difference between averaged values of Z_{DR} for small changes in elevation angles should be minimal.

For several rain events, we identify range locations where $1 < R(K_{DP}) < 5$ mm h^{-1} and partition these range gates into 1° azimuthal intervals. Mean Z_{DR} values for these intervals are computed and examined as a function of azimuth. 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 azimuth. This is provided that the averaging procedure is performed over a sufficiently large volume of data. Data are filtered using a simple fuzzy logic hydrometeor classification approach to remove ground clutter contaminants. Only gates in close proximity to the radar are averaged to mitigate melting layer contamination for rain events.

The hypothesis that PBB is responsible for the azimuthal modulation of Z_{DR} observed with the Cimarron radar at the 0.5° tilt 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} measured at the unblocked (1.5°) and blocked (0.5°) elevation angles is shown in Fig. 3 for several Cimarron events. The observed difference between the elevation angles remains relatively stable for several years.

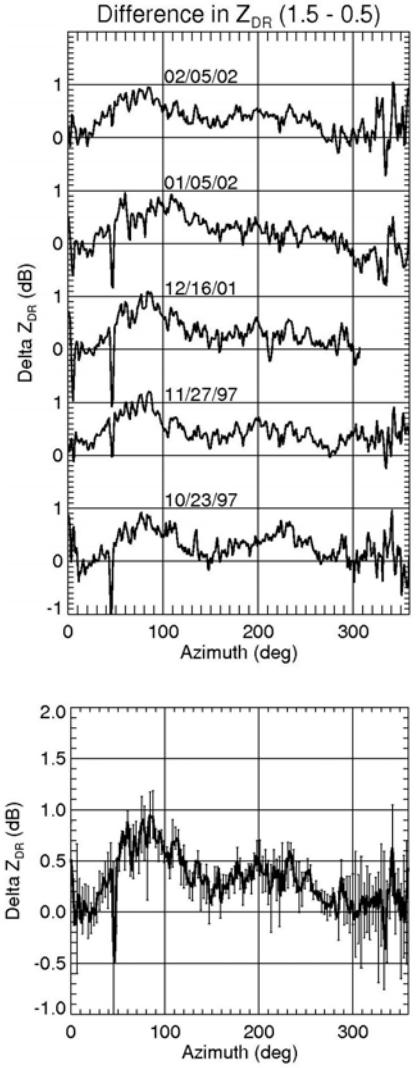

Fig. 3. Difference between the mean azimuthal dependencies of Z_{DR} at the 1.5° and 0.5° elevation angles for 5 Cimarron radar events (top). Mean azimuthal dependence for all 5 events (bottom). Error bars indicate the range of variation in the difference field.

The Z_{DR} bias due to PBB is unacceptably high and approaches 0.8 dB in certain azimuthal sectors. The origin of the Z_{DR} bias associated with PBB may stem from a variety of sources. For example, the antenna beams at the H and V polarizations may not be 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. However, the most likely cause stems from semi-transparent obstacles (like nearby trees), which might have different degrees of transparency for H and V radiation similar to polarimetric grids. The magnitude of the bias is particularly noteworthy for a radar located in the Great Plains, without rugged or mountainous terrain in close proximity.

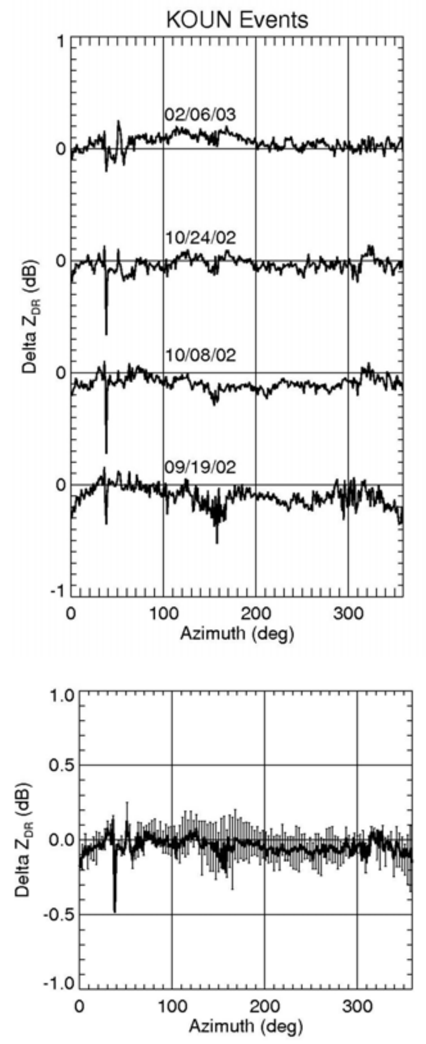

Fig. 4. As in Fig. 3., but for 4 events observed by the KOUN radar.

The same methodology was applied to the KOUN polarimetric radar data (Fig. 4). The difference in the mean Z_{DR} at the two elevations for these events is 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˚, the locations of known structures. The standard deviation of the Z_{DR} difference is 0.08 dB. Moreover, there is no PBB except for a few isolated directions.

The suggested calibration of Z_{DR} in the presence of PBB can be formulated as follows. Initially, absolute calibration of Z_{DR} is performed at high (unobstructed) elevation angles. 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, as outlined in the previous section. To address PBB, regions of light rain or dry snow should be identified using a polarimetric classification algorithm and K_{DP} measurements that are not biased by PBB. Once appropriate scatterers are identified, the mean value of Z_{DR} corresponding to these scatterers should be computed as a function of azimuth at the potentially blocked and unblocked elevations. At the azimuths where the discrepancy in the 'blocked' and 'unblocked' Z_{DR} exceeds 0.2 – 0.3 dB, the Z_{DR} values at the lower elevation should be corrected.

b. *Self-consistency approach for Z calibration in the presence of PBB*

After Z_{DR} is calibrated using techniques described in the previous sections, the principle of self-consistency among Z, Z_{DR}, and K_{DP} in the rain medium can be applied as a means to estimate a bias in Z. This bias in Z is also expected to change with azimuth as a function of PBB. To investigate the Z bias caused by PBB for the Cimarron radar, we slightly modify the self-consistency approach outlined above by integrating over 5˚ azimuthal sectors within the ARS network. It is assumed that the 5˚ increments are sufficient to resolve azimuthal modulation of the Z bias caused by PBB. Additional temporal averaging was utilized to offset this change in the spatial domain.

Figure 5 contains a summary of the Z bias estimates from direct KTLX and Cimarron comparison and consistency retrievals for 5 stratiform rain events. Each event contains a minimum of two consecutive hours of hourly KTLX-Cimarron rainfall estimate comparisons and a minimum of 3 hours of accumulated radar data for the consistency-based calibration. Direct comparisons were obtained by comparing one-hour rainfall accumulations over ARS locations estimated from both radars using a conventional R(Z) algorithm and determining how the difference between the two is projected into Z. The bias of Z exhibits a well-pronounced azimuthal modulation, even within a relatively narrow sector of less than 40˚.

Two consistency relations, valid primarily for stratiform rain, are offered: one relation is found in (3) and the other based on measured DSD and Brandes et al. (2002) drop shapes:

$$Z = 46.5 + 10.5 \log(K_{DP}) + 1.67\, Z_{DR.} \tag{5}$$

The two consistency-based estimates (solid and dashed lines) of the Z offset agree within 0.5 dB of each other. Azimuthal dependencies of the bias obtained from the consistency relations and direct Cimarron – KTLX comparisons (diamonds) also agree quite well. There are some indications that the operational KTLX radar could be miscalibrated (e.g., KTLX radar was likely negatively biased prior to Fall 2000). This might partially explain why the consistency estimates show more negative biases in Z prior to Fall 2000 (three upper panels in Fig. 5) and less negative biases after Fall 2000 (two lower panels in Fig. 5) compared to the direct Cimarron – KTLX estimates. It is speculated that if the reference KTLX radar was perfectly calibrated, then the average differences in the estimates of Z bias by the two methods (consistency and direct comparison) are within 2 dB.

4. Test of the real-time algorithm

The consistency calibration was implemented in a real-time algorithm that was tested using several JPOLE rain events. The area domain was increased to include ranges between 30 and 100 km and data spanning all azimuths. These ranges were selected to mitigate ground clutter and melting layer contaminants while maintaining high variable resolution. An automatic hydrometeor classification procedure was incorporated to ensure the integration of data consistent with rain. Automatic selection of an optimum consistency relation was performed between relations “LD” (3) and “SD” (4) based on the results of quality control measures (Ryzhkov et al. 2004).

The estimate of Z bias was updated continuously during data acquisition once the area-time integral of K_{DP} exceeds a sufficiently high threshold. This threshold was used to ensure that statistical errors due to noisiness in K_{DP} measurements are substantially reduced.

Fig. 6 displays the results of the real-time consistency calibration for three events during JPOLE in 2003 (May 14, May 20, and June 12). Each curve in Fig. 6 represents the estimated bias of Z as a function of time. If the consistency method is robust, then one has to expect relatively small changes in the Z bias estimate during individual rain events. As Fig. 6 suggests, such variability is within 1 dB for several hours, and these Z bias estimates typically agreed with the measured KTLX-KOUN offset to within 1.5 dB.

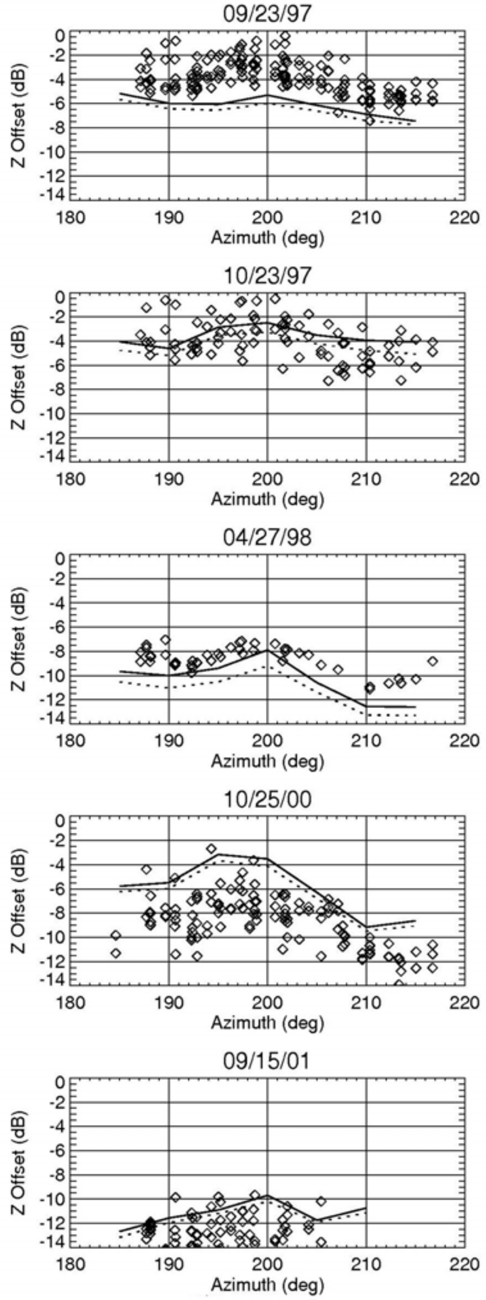
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Fig. 5. Offset of Z as a function of azimuth for 5 rain events. Diamonds indicate results of direct comparisons of Z from the Cimarron and WSR-88D data (Cimarron-KTLX). The curves represent results of consistency-based retrievals for the disdrometer relation (solid lines) and KOUN radar relation (dashed lines).

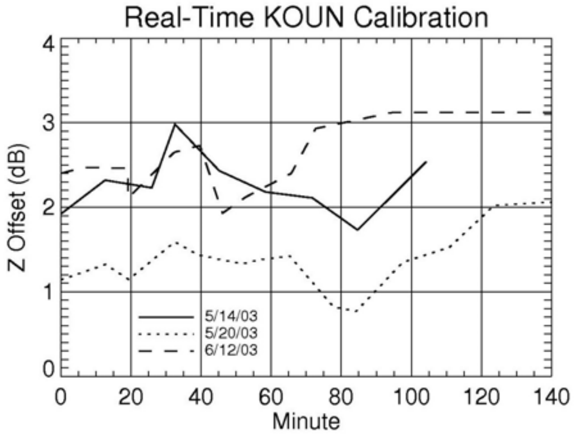

Fig 6. Offset of Z as a function of update time for 3 rain events. The curves represent results of real-time consistency Z bias retrievals using the best available relation among "LD" (3) and "SD" (4) based on quality control. Positive values indicate a positive Z bias of the KOUN radar.

5. Conclusions

Polarimetric weather radar can be calibrated using natural scatterers such as rain and dry snow. This calibration can be performed for individual precipitation events in the process of real-time data acquisition. This calibration is possible even if the radar beam is partially blocked. The accuracy of calibration is to within 2 dB and 0.2 dB for Z and Z_{DR} for partially blocked radar. The accuracy of calibration is to within 1-1.5 dB and 0.1 dB for Z and Z_{DR} using unblocked radar provided quality control is performed on Z bias estimates.

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