1. INTRODUCTION

Advantages of dual-polarization radar for rainfall estimation and radar echo classification have been proven in many research studies. Operational demonstration occurred during the Joint Polarization Experiment (JPOLE) using the polarimetric prototype of the WSR-88D radar (Ryzhkov et al. 2005). Based on the JPOLE results, the US National Weather Service plans to add soon polarimetric capability to all operational WSR-88D radars.

The JPOLE success also encouraged national services around the world to consider polarimetric upgrade of their radars operating either at the same frequency band (i.e., S band) or at shorter wavelength (e.g., C band). Other efforts are directed towards possible utilization of inexpensive X-band polarimetric radars to complement existing WSR-88D radars in the regions of poor coverage (as "gap fillers") or for monitoring rainfall over small areas. Therefore, adaptation of existing S-band polarimetric algorithms for precipitation estimation and radar echo classification for shorter wavelengths is an important practical issue.

At shorter wavelengths, effects of attenuation, resonance scattering, cross-coupling between orthogonal polarizations due to simultaneous transmission/reception become more significant compared to S band. Nonuniform beam filling has much larger impact on the quality of polarimetric measurements at shorter wavelengths, particularly for smaller radars with broader beams.

In this study, we address these problems by simulating realistic fields of polarimetric variables in rain at C and X bands based on the measured fields obtained from the dual-polarization WSR-88D radar. Polarimetric algorithms for radar echo classification and DSD retrieval are used for such simulation.

2. ATTENUATION AND RESONANCE EFFECTS

Here we briefly summarize the differences in radar scattering characteristics at S, C, and X bands in rain using theoretical simulations and large statistics of disdrometer measurements in central Oklahoma. The theoretical simulations are performed assuming that the aspect ratio of raindrops a/b depends on a drop equivolume diameter D according to the formula suggested by Brandes et al. (2002), the width of the canting angle distribution is $10^\circ$ (Ryzhkov et al. 2002), and temperature of raindrops is 20°C.

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Fig. 1. Dependencies of $Z_{DR}$, $K_{DP}$, $A_h$, and $A_{DP}$ on raindrop equivolume diameter at S, C, and X bands ($T = 20^\circ$C).
Fig. 1 illustrates dependencies of differential reflectivity $Z_{\text{DR}}$, specific differential phase $K_{\text{DP}}$, specific attenuation $A_{\text{h}}$, and specific differential attenuation $A_{\text{DP}}$ on equivolume diameter of individual raindrop at S band ($\lambda = 11.0$ cm), C band ($\lambda = 5.45$ cm), and X band ($\lambda = 3.2$ cm). It is evident that the resonance effects are less pronounced at X band compared to C band due to larger imaginary part of dielectric constant at X band ($\varepsilon = 72.8 - j22.4$ and $62.1 - j32.0$ at C and X bands respectively). Indeed, the resonance effect is a result of interference of the electromagnetic waves reflected from the near and rear sides of the raindrop. If losses in the raindrop medium are high (as at X band) then the wave reflected from the rear side of the raindrop is significantly attenuated and interference is less pronounced. Because imaginary part of $\varepsilon$ decreases with temperature, the resonance becomes stronger at higher temperatures of raindrop.

The resonance effects at C band can result in anomalously high $Z_{\text{DR}}$, negative $K_{\text{DP}}$, and negative $A_{\text{DP}}$ that are not possible at S or X bands. Raindrops with sizes exceeding 5 mm are not very common in rain but their impact on most radar variables (especially $Z_{\text{DR}}$) is quite significant. We resort to the multi-year statistics of the 2D-video disdrometer measurements of drop size distributions (DSD) in Norman, OK to assess the impact of large drops on various radar variables at different radar frequencies. The dataset containing 27920 1-min DSD measurements was used in our estimation.

Fig. 2 exhibits a scatterplots of differential reflectivities at S band ($Z_{\text{DR}}(S)$) versus differential reflectivities at C and X bands ($Z_{\text{DR}}(C)$ and $Z_{\text{DR}}(X)$) computed from disdrometer data. It is clear that the difference between $Z_{\text{DR}}(S)$ and $Z_{\text{DR}}(C)$ becomes significant for $Z_{\text{DR}}(S) > 2$ dB, i.e., for DSD dominated by large drops. For such DSDs, the difference in $Z_{\text{DR}}$ at S and X bands is small, but rain with $Z_{\text{DR}}(S)$ between 1.0 and 2.5 dB exhibits noticeably higher $Z_{\text{DR}}(X)$ than $Z_{\text{DR}}(S)$.

The magnitude of the cross-correlation coefficient $\rho_{hv}$ is also affected by the resonance effects at C band (Fig. 3). The cross-correlation coefficient might drop well below 0.98 at C band in pure rain, whereas the 0.98 $\rho_{hv}$ threshold can be safely used as a cut-off value for rain at S and X band.

It is interesting that backscatter differential phase $\delta$ can be significantly larger at C than at X band for certain types of DSD that contain enough raindrops with sizes exceeding 5 mm (Fig. 4). According to disdrometer data, DSDs with larger drops (i.e. with $Z_{\text{DR}}(S) > 2.5$ dB) constitute only 1 – 2% of all DSDs in the dataset but they are associated with about 10% of total rainfall. It is also known that the disdrometers (unlike radars) commonly underestimate the number of large drops in rain spectrum due to their relatively low concentrations and small size of the disdrometer sampling volume. Hence, the impact of large drops on radar measurements might be more significant than revealed from disdrometer data.

3. NONUNIFORM BEAM FILLING (NBF)

Nonuniform beam filling affects all radar variables but the largest impact is on measurements of differential phase and cross-correlation coefficient. Ryzhkov and Zrnic (1998), Gosset (2004), and Ryzhkov (2005)
Fig. 4 Scatterplots of backscatter differential phase \( \delta \) versus \( Z \) at C and X bands as derived from disdrometer data demonstrated that variations of differential phase \( \Phi_{DP} \) and radar reflectivity \( Z \) within the radar resolution volume may cause significant perturbations of the radial profile of \( \Phi_{DP} \).

The perturbation \( \Delta \Phi_{DP} \) can be estimated using the following formula (Ryzhkov 2005):

\[
\Delta \Phi_{DP} \approx 0.02 \Omega^2 \left( \frac{dZ_{HV}}{d\theta} \frac{d\Phi_{DP}}{d\theta} + \frac{dZ_{HV}}{d\varphi} \frac{d\Phi_{DP}}{d\varphi} \right),
\]

where \( \Omega \) is a one-way 3 dB antenna pattern width, and \( Z_{HV} \) is determined as \( 10 \log \left[ \rho_{hv} (Z_{h}Z_{v})^{1/2} \right] \) (\( Z_{h,v} \) are radar reflectivity factors at horizontal and vertical polarizations expressed in linear scale). Eq (1) was derived assuming linear dependencies of \( Z_{HV} \) and \( \Phi_{DP} \) on azimuthal and elevation angles \( \theta \) and \( \varphi \) within the radar resolution volume and Gaussian shape of the radar antenna pattern.

NBF also reduces the magnitude of the cross-correlation coefficient \( \rho_{hv} \). Such a reduction is described by the following expression (Ryzhkov 2005):

\[
\rho_{hv}^{(b)} = \rho_{hv} \exp\left[ -0.045 \Omega^2 \left( \frac{d\Phi_{DP}}{d\theta} \right)^2 + \left( \frac{d\Phi_{DP}}{d\varphi} \right)^2 \right].
\]

Since differential phase and its gradients are directly proportional to the radar frequency, the impact of NBF is much more pronounced at C and X bands. Similarly, increasing an antenna beamwidth might result in significant increase of \( \Delta \Phi_{DP} \) and the drop of \( \rho_{hv} \) in the presence of highly localized convection.

4. DSD RETRIEVAL

In order to compare polarimetric signatures in rain at different radar wavelengths we developed a simulator that takes the fields of polarimetric data collected with the KOUN WSR-88D radar and convert these into the fields of radar variables that should be expected at C and X bands. Such simulation implies DSD retrieval from the S-band polarimetric data. The DSD retrieval should be conducted only in the areas of rain, hence, the classification of radar echo is carried out prior to the retrieval. Classification is based on the principles of fuzzy logic as described by Schuur et al. (2003) and Ryzhkov et al. (2005).

We assume that DSD has a constrained Gamma form suggested by Zhang et al. (2001) and Brandes et al. (2004):

\[
N(D) = N_0 \mu^\Lambda \exp(-\Lambda D), \quad (3)
\]

where

\[
\Lambda = 0.0365 \mu^2 + 0.735 \mu + 1.935. \quad (4)
\]

According to Brandes et al. (2004), DSD is truncated at the drop size \( D_{\text{max}} \) that depends on \( Z \):

\[
D_{\text{max}} = 0.947 + 6.8110^{-3}Z + 4.2510^{-3}Z^2 - 1.1210^{-4}Z^3 + 1.2510^{-6}Z^4 + 1.0 \quad (5)
\]

where \( Z \) is expressed in dBZ.

Our analysis shows that DSDs characterized by anomalously large \( Z_{DR} \) and moderate or low \( Z \) often observed in the radar data can not be matched with constrained Gamma DSD determined by Eq (3-5) regardless of the choice of \( \mu \). In such cases, we assume that the constrained Gamma DSD is truncated not only at higher end but also at lower end. In fact, quite often high values of \( Z_{DR} \) are attributed to the absence of small drops rather than to the presence of big drops. This is often the case in the updraft areas where small drops are suspended aloft and only few very big raindrops can fall through the updraft to the ground.

If \( Z_{DR} \) is too large (for a given \( Z \)) to fit any constrained Gamma DSD defined with (3) – (5), we assume that the DSD has a form determined by (3) and (4) but with fixed \( \mu = -2 \) and it is truncated at \( D_{\text{max}} \) at lower end and at \( D_{\text{max}} + D_{\text{min}} \) (not exceeding 8 mm) at higher end. In other words, \( \mu \) is fixed but a newly introduced parameter \( D_{\text{max}} \) is allowed to vary.

Following this methodology, we generated look-up tables of the DSD parameters \( \mu, \Lambda, N_0, D_{\text{min}}, \) and \( D_{\text{max}} \) for any given pair of the measured \( Z \) and \( Z_{DR} \).

5. EXAMPLE OF SIMULATION

After DSD parameters are determined, we can generate fields of all radar variables at S, C, and X bands using scattering computations as described in section 2. Nonuniform beam filling effects are accounted for by examining \( Z_{HV} \) and \( \Phi_{DP} \) differences between
adjacent radials separated by $1^\circ$ in the horizontal and vertical directions.

As an example, we present results of simulations for rain event which occurred on May 13, 2004. Fields of $Z$ and $Z_{DR}$ at lowest elevation $0.5^\circ$ in the area of interest are displayed in Fig. 5. The radar echo was classified as pure rain everywhere in the selected area. We focus our analysis on the region of convective rain in the northern part of the echo. This region is marked with high $Z_{DR}$ observed at the periphery of convective cells. Figs. 6–8 illustrate radial profiles of different radar variables along the ray indicated in Fig. 5.

As expected, radar reflectivities at C and X bands are affected by attenuation in the major convective cell centered at the distance 86.5 km from the radar (Fig. 6a). Radial profiles of $Z_{DR}$ at C and X bands reflect combined effect of differential attenuation and the resonance (Fig. 6b). C-band $Z_{DR}$ is much higher than S-band $Z_{DR}$ in the main reflectivity core. $Z_{DR}(C)$ becomes lower than $Z_{DR}(S)$ behind the core where the effect of differential attenuation is dominant. $Z_{DR}(X)$ is slightly higher than $Z_{DR}(C)$ at 95 km due to the X-band resonance effect that offsets stronger differential attenuation at shorter wavelength.

Nonuniform beam filling (NBF) has almost negligible impact on $Z$ and $Z_{DR}$. However, this is not the case for $\Phi_{DP}$ and $\rho_{hv}$. Differential phase exhibits nonmonotonic behavior as a function of range at all three radar frequencies (Fig. 7). The measured radial
6.1 Attenuation correction

Attenuation correction at C and X bands presents more serious challenge compared to S band where attenuation is only occasionally a problem. Existing methods for attenuation correction using differential phase $\Phi_{DP}$ stipulate that the ratios $\alpha = A_r/K_{DP}$ and $\beta = A_{DP}/K_{DP}$ are relatively independent of DSD and the biases of $Z$ and $Z_{DR}$ can be obtained from the following relations (Bringi et al. 1990):

$$\Delta Z = -\alpha \Phi_{DP}$$  \hspace{1cm} (6)

and

$$\Delta Z_{DR} = -\beta \Phi_{DP}$$  \hspace{1cm} (7)

In order to apply formulas (6) and (7) for attenuation correction at C and X bands, the $\delta$ part of $\Phi_{DP}$ should be identified and removed. This is hard to do because of (a) high noisiness of the differential phase in the parts of the storm where $p_{hv}$ is relatively low and (b) additional oscillations of $\Phi_{DP}$ that are caused by nonuniform beam filling and have similar appearance as $\delta$ in the radial profiles of differential phase (see Fig. 7). Another problem is the dependence of the coefficients $\alpha$ and $\beta$ in Eq (6) and (7) on temperature and mean raindrop shape as well as their high variability in the presence of large drops (i.e., for $Z_{DR} > 2$ dB).

The latter problem was first recognized by Carey et al. (2000). They recommend to identify the zones of large drops using estimates of $p_{hv}$ and $\delta$ and utilize different (but fixed) coefficients $\alpha$ and $\beta$ in these regions. This approach is not applicable everywhere because (a) it is very difficult to estimate $\delta$ reliably and (b) the coefficients $\alpha$ and $\beta$ are highly variable in the regions of large drops for which the resonance effects can be significant, especially at C band (see Fig. 1).

An alternate approach for attenuation correction of $Z$ was introduced by Testud et al. (2000) (ZPHI method). The ZPHI method aims at estimating radial profile of specific attenuation $A_r$ with the difference between the starting and ending values of $\Phi_{DP}$ used as a constraint.

The ZPHI procedure also implies that the ratio $\alpha = A_r/K_{DP}$ is constant and fixed which is not the case in the areas of large drops. Bringi et al. (2001) proposed to generalize the ZPHI method by allowing the ratio $\alpha$ to vary. According to their approach, the appropriate value of $\alpha$ should be determined by matching the measured radial profile of $\Phi_{DP}$ and a “constructed” profile of $\Phi_{DP}$ computed as

$$\Phi_{DP}^c(r,\alpha) = \frac{2}{\alpha \rho_{hv}} \int_{r_0}^{r} A_s(s,\alpha) ds$$  \hspace{1cm} (8)

This scheme, however, may not work if radial profile of the measured $\Phi_{DP}$ is highly perturbed due to several factors discussed earlier.

Summarizing, we believe that although some studies report on successful attenuation correction at C and X bands (e.g., Carey et al. 2000; Le Bourar et al. 2001, Matrosov et al. 2002), the correction methods should be more carefully tested, particularly in the cases of strong isolated convection.

6.2 Classification

Differential reflectivity $Z_{DR}$ and cross-correlation coefficient $p_{hv}$ prove to be most useful polarimetric variables for classification of radar echo. One has to keep in mind that $Z_{DR}$ in pure rain at C and X bands might be noticeably higher than the corresponding $Z_{DR}$ at S band (Fig. 2). On the other hand, $p_{hv}$ in rain at C band can drop dramatically if large drops are present (Fig. 3). As a result, the areas of large drops associated with updrafts or melting hail may be very efficiently identified with polarimetric measurements at C band. In any case, the parameters of membership functions in the fuzzy logic classification algorithm should be changed accordingly.
6.3 Rainfall estimation

To measure rainfall reliably, intrinsic (nonattenuated) Z and \( Z_{DR} \) should be estimated with the accuracy of 1 dB and 0.1 – 0.2 dB respectively. It is not obvious at the moment that the correction methods at C and X bands can provide an estimate of attenuation biases of Z and \( Z_{DR} \) with such a high precision. Therefore, the role of \( K_{DP} \) for rainfall estimation at shorter wavelengths might be even more important than at S band. However, as already mentioned, differential phase should be utilized with caution at shorter wavelengths because of possible contribution from \( \delta \), negative \( K_{DP} \) due to resonance effects, nonuniform beam filling, and large statistical fluctuations of \( \Phi_{DP} \) and \( K_{DP} \) caused by lower \( \rho_{hv} \). As our simulations show, these problems can be more serious at C band than at X band.

More rapid range degradation of the quality of polarimetric classification and rainfall estimation at shorter wavelengths is a natural consequence of stronger attenuation. We suspect, however, that in the cases of isolated convection it is not a loss of sensitivity due to attenuation but beamwidth effects that might restrict the use of polarimetric methods on short-wavelength radars (particularly with antenna beams wider than 1°).

6.4 Cross-coupling

Simultaneous transmission and reception of horizontally and vertically polarized waves is a preferable choice technique for dual-polarization weather radar (Doviak et al. 2000). One of the side effects of such a choice is cross-coupling between orthogonally polarized waves. Cross-coupling depends on depolarizing properties of propagation media. Preliminary results of our simulations show that it is negligible in rain at all three radar wavelengths examined.

Nevertheless, cross-coupling can be noticeable in such highly depolarizing media as hail and especially crystals in the upper parts of the thunderstorm clouds. We have clear evidence of that at S band. Because depolarization propagation effects are wavelength-dependent, one might expect more serious problems in nonrain medium at shorter wavelengths.

7. REFERENCES


