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VALIDATION OF POLARIMETRIC METHODS FOR ATTENUATION CORRECTION AT C BAND

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1. INTRODUCTION

Polarimetric methods for attenuation correction of radar reflectivity Z and differential reflectivity Z_{DR} utilize measurements of differential phase Φ_{DP} which is immune to attenuation (Bringi and Chandrasekar 2001). Simplified versions of the attenuation correction techniques assume that the coefficients of proportionality α and β between the Z and Z_{DR} biases and Φ_{DP} do not vary much. However, at C band these are highly variable in convective cells containing large raindrops and hail due to effects of resonance scattering (Carey et al. 2000, Ryzhkov et al. 2006). More sophisticated schemes for attenuation correction attempt to estimate the coefficients α and β in such "hotspot" cells using additional constraints.

In this paper, we evaluate the performance of the attenuation correction techniques with different degree of complexity using C-band data collected with the Environment Canada King radar in Southern Ontario, Canada, and the Enterprise Electronics Corporation (EEC) Sidpol radar in Alabama, USA.

2. ATTENUATION CORRECTION TECHNIQUES

First polarimetric technique for attenuation correction of Z and Z_{DR} was suggested by Bringi et al. (1990). According to this methodology, the biases of Z and Z_{DR} are estimated from simple formulas

$$\Delta Z = \alpha \Phi_{DP} \quad \text{and} \quad \Delta Z_{DR} = \beta \Phi_{DP} \,, \qquad (1)$$

where the coefficients α and β are supposed to be constant. The coefficient α is the ratio of specific attenuation A_h and specific differential phase K_{DP}, whereas the coefficient β is the ratio of specific differential attenuation A_{DP} and K_{DP}. Testud et al. (2000) proposed another correction algorithm for Z (the "ZPHI" rain-profiling algorithm) which also assumes a fixed coefficient α. Later on, Bringi et al. (2001) extended the ZPHI method to optimize the coefficients α and β by examining radial profile of Φ_{DP} and imposing constraint on the corrected value of Z_{DR} at the far side of attenuating rain cell.

Ryzhkov et al. (2006) suggested another modification of the ZPHI scheme at C band according to which the ratio α is assumed to be highly variable in the "hotspots" containing large drops and / or hail and is equal to a constant climatological value α_0 outside of "hotspots". The "hotspot cell" is identified if the radar reflectivity factor corrected for attenuation according to (1) with $\alpha = \alpha_0$ exceeds 45 dBZ and the cross-correlation coefficient ρ_{hv} exceeds 0.8 at a number of consecutive range locations extending to at least 2 km. It is assumed that in the "hotspot" $\alpha = \alpha_0 + \Delta\alpha$, where Δα is determined from the iterative procedure specified below.

A number of range profiles of specific attenuation A_h parametrized by Δα are computed from equation

$$A_h(r,\Delta\alpha) = \frac{[Z_h(r)]^b [10^{0.1bC} - 1]}{I(r_0;r_m) + [10^{0.1bC} - 1] I(r;r_m)} \,, \qquad (2)$$

where

$$C = \alpha_0 \Delta\Phi_{DP}(r_0,r_m) + \Delta\alpha \Delta\Phi_{DP}(HS) \,, \qquad (3)$$

$$I(r_0;r_m) = 0.46\, b \int_{r_0}^{r_m} [Z_h(s)]^b ds \,, \qquad (4)$$

$$I(r;r_m) = 0.46\, b \int_{r}^{r_m} [Z_h(s)]^b ds \,, \qquad (5)$$

In (2) – (5), b = 0.8 and Z_h is the measured (uncorrected) reflectivity expressed in linear units. In (3), $\Delta\Phi_{DP}(r_0,r_m)$ is total increase in Φ_{DP} along the ray where attenuation occurs and $\Delta\Phi_{DP}(HS)$ is the part of total Φ_{DP} increase attributed to "hotspot cells".

The parameter Δα is defined from the iterative process of incrementing Δα until the following condition is satisfied:

$$\int_{OHS} A_h(s,\Delta\alpha) ds = \frac{\alpha_0}{2} \Delta\Phi_{DP}(OHS) \quad , \qquad (6)$$

where integration is performed over the gates outside of hotspots (OHS) and

$$\Delta\Phi_{DP}(OHS) = \Delta\Phi_{DP}(r_0;r_m) - \Delta\Phi_{DP}(HS) \qquad (7)$$

Finally, the corrected radar reflectivity factor is expressed as

$$Z_H^{(c)}(r) = Z_H(r) + 2\int_{r_0}^{r} A_h(s,\Delta\alpha) ds \qquad (8)$$

where Z_H is in dBZ and $A_h(s,\Delta\alpha)$ is the profile of specific attenuation determined from (6).

Similarly, it is assumed that in the "hotspot" $\beta = \beta_0 + \Delta\beta$, i.e., the ratio A_{DP}/K_{DP} is variable. The bias of Z_{DR} in the far side of the attenuation interval along the radar beam is determined as follows

$$\Delta Z_{DR}(r) = 2\int \beta(s) K_{DP}(s) ds = \beta_0 \Phi_{DP}(r) + \Delta\beta\, \Delta\Phi_{DP}(HS) \qquad (9)$$

In (9),

$$\Delta\beta = \frac{Z_{DR}^{(th)} - \min(Z_{DR}(r,\beta_0))}{\Delta\Phi_{DP}(HS)} \qquad (10)$$

and

$$Z_{DR}(r,\beta_0) = Z_{DR}(r_0) + \beta_0 \Phi_{DP}(r) \,. \qquad (11)$$

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The parameter $\Delta\beta$ is determined in such a way that the minimal corrected value of Z_{DR} in the shadow of "hotspot" cells is equal to $Z_{DR}^{(th)}$ = 0.1 – 0.2 dB.

3. RESULTS OF ATTENUATION CORRECTION IN CANADA AND ALABAMA

In this study, we evaluate the performance of the simplistic "base" version of the attenuation / differential attenuation correction given by Eq (1) and the "advanced" one which is specified by Eqs (2) – (11). C-band polarimetic data collected by the King radar in Southern Ontario, Canada, and the EEC Sidpol radar in Alabama, USA, are used for testing and validation. For evaluation, we have selected 7 storms (4 in Canada and 3 in Alabama) which produce substantial attenuation for 1 – 2 hours. These storms are listed in Table 1.

Table 1. Variability of α and β in 7 storms

Date	Median α	Median β	Comments
Alabama storms			
10/17/2006	0.08 – 0.09	0.008 – 0.010	Tropical rain
11/15/2006	0.09 – 0.10	0.016 – 0.025	Rain w hail
03/01/2007	0.09 – 0.11	0.009 – 0.011	Tornado
Canada storms			
06/14/2005	0.11 – 0.16	0.013 – 0.039	Small hail
08/19/2005	0.08 – 0.11	0.009 – 0.014	Rain
06/28/2006	0.16 – 0.22	0.07 – 0.09	Large hail
04/23/2007	0.15 – 0.21	0.03 – 0.06	Rain w hail

The "background" or climatological value of α_0 = 0.06 dB/deg has been selected in our analysis for the storms in both geographical areas, whereas the "background" values of β_0 = 0.017 and 0.010 deg/km were used in Canada and Alabama respectively. It was found that the climatological value of β_0 is more affected by the difference in prevalent rain regimes in Canada (more continental) and Alabama (more tropical) than the climatological value of α_0.

An example of anomalously severe attenuation produced by a tiny "hotspot" within the hailstorm observed in Canada on 06/28/2006 is illustrated in Fig. 1. The size of hail observed on the ground was between 1 and 2.5 cm. Relatively small core (about 6 km in diameter) within the storm cell causes attenuation of 20 dB and differential attenuation of more than 12 dB! The corresponding increase in differential phase is rather modest – only 120°. The "base" correction technique falls far short of removing the biases in Z and Z_{DR} (blue curves). The "advanced" methodology yields α = 0.20 dB/km and β = 0.12 dB/km within the "hotspot" identified between ranges 47 and 53 km from the radar. These are more than 3 and 7 times larger than their "background" values.

It is notable that Z_{DR} within the hailstorm core remains very high after appropriate correction for differential attenuation is performed (red curve in Fig. 1b) because melting hail is apparently mixed with large raindrops which produce anomalously high Z_{DR} at C band due to the effects of resonance scattering.

Dramatic difference in attenuation-related biases in Z and Z_{DR} in typical tropical rain on 10/17/2006 observed in Alabama and in continental rain on

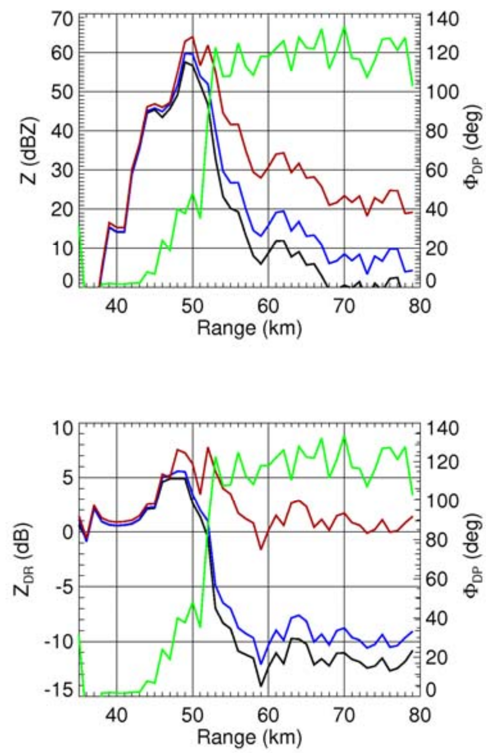

Fig. 1. Radial profiles of the measured Z and Z_{DR} (black lines), corrected Z and Z_{DR} using the "base" technique (blue lines), corrected Z and Z_{DR} using the "advanced" technique (red lines), and Φ_{DP} (green lines) in the case of 06/28/2006; 1630 UTC, El = 0.5°, Az = 15°.

04/23/2007 in Canada is illustrated in Figs. 2 and 3. Although maximal values of Φ_{DP} for both storms are quite comparable (more than 400°), differential attenuation in continental rain is almost 10 dB larger due to the presence of large raindrops and melting hail. This is further substantiated by noticeably higher values of corrected Z_{DR} in the Canadian storm.

The "base" attenuation correction technique yields very similar attenuation bias in Z for both cases (blue curves) exceeding 25 dB at the end of propagation path. The "base" technique underestimates actual attenuation by 11 dB in the continental case and by 5 dB in the tropical case. Because tropical rain contains much smaller number of large drops than the continental one, the difference in attenuation correction results between the "base" and "advanced" techniques is significantly smaller in the tropical case.

We performed statistical analysis of the coefficients α and β in "hotspots" for all 7 storms. For each radar scan, the median values of α and β corresponding to different azimuths at elevation 0.5° have been estimated. The ranges of median values for each event are presented in Table 1. They exhibit significant within-the-storm and between-the-storms variability of α and β. Variations in differential attenuation are especially large. It is not surprising that both α and β are higher in the storms containing melting hail. Since most storms in Alabama do not produce much hail aloft and if such hail is generated it melts more rapidly in a humid environment, the coefficients α and β are generally

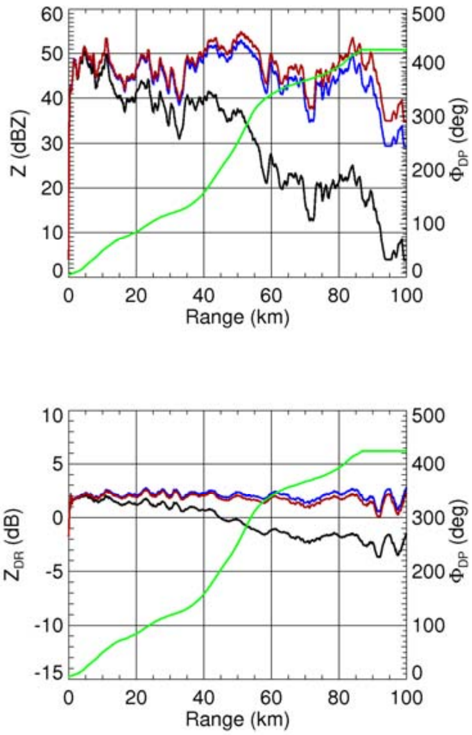

Fig. 2. Same as in Fig. 1 but for the case on 10/17/2006 in Alabama; 1802 UTC, Az = 296°.

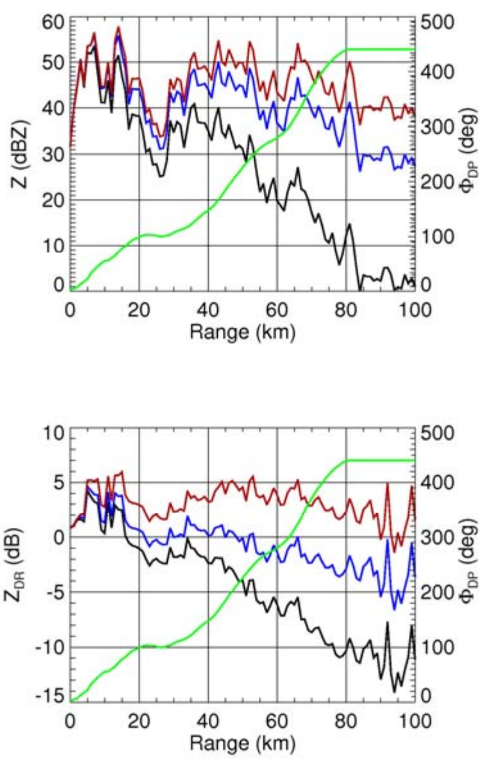

Fig. 3. Same as in Fig. 1 but for the case on 04/23/2007 in Canada; 2020 UTC, Az = 230°.

lower in Alabama compared to Southern Ontario.

4. VALIDATION OF THE ATTENUATION CORRECTION TECHNIQUES

The quality of Z correction was evaluated using consistency with K_{DP} which is not affected by attenuation, comparison with S-band radar measurements, and spatial / temporal continuity of the corrected Z fields. The Z_{DR} correction was validated using spatial / temporal continuity and checking the absence of artificially looking radial spikes of overcorrected or undercorrected Z_{DR} in the fields of differential reflectivity. The data from nearby S-band WSR-88D radars in Buffalo and Panama City were used to validate attenuation correction of Z.

The efficiency of attenuation correction with the "advanced" technique is illustrated in Fig. 4 and 5 where the fields of the measured Z and Z_{DR}, corrected Z and Z_{DR}, Φ_{DP}, and ρ_{hv} are displayed for the Canada storm on 04/23/2007 and Alabama storm on 11/15/2006. As Figs. 4 and 5 show, the algorithm efficiently restores negatively biased Z and Z_{DR} in the azimuthal sectors of enhanced attenuation marked by large increase of Φ_{DP}.

In order to quantify the quality of attenuation correction of Z, we convert measured and corrected radar reflectivity factors at C band into rain rates and compare them with rain rates computed from the measured C-band K_{DP} and Z obtained from the closest S-band WSR-88D radar. We use the following R(Z) and R(K_{DP}) relations:

$$R(Z(S)) = 1.70\,10^{-2} Z_h^{0.714} \qquad (12)$$

$$R(Z(C)) = 1.69\,10^{-2} Z_h^{0.717} \qquad (13)$$

$$R(K_{DP}) = 25.1 |K_{DP}|^{0.777}\ \mathrm{sign}(K_{DP}) \qquad (14)$$

Relations (13) and (14) have been obtained from C-band simulations using large statistics of DSD in Oklahoma, whereas Eq (12) represents the standard R(Z) relation used for WSR-88D.

Fields of rain rates corresponding to the composite plots of radar variables in Fig. 4 and 5 are displayed in Fig. 6 and 7. Three fields of rain rates presented in Fig. 6 and 7 are retrieved from the measured Z (no correction), corrected Z if old ("base") correction is performed, and corrected Z if new ("advanced") correction is utilized. In addition, rain rates estimated from K_{DP} and S-band Z are shown for comparison.

The Buffalo WSR-88D radar is located 130 km SE of the King radar, whereas the Panama City WSR-88D radar is at the distance of 81 km from the Sidpol radar. The location of the Panama City radar is marked with a cross in Fig. 7.

In both cases, the R(Z) estimate after "advanced" attenuation correction is implemented is in better agreement with the R(K_{DP}) and R(Z(S)) estimates than the one retrieved from Z which is corrected using "base" correction technique. The latter definitely tends to underestimate rain rate. Note that reliable comparison with S-band R(Z) is possible only in the areas where the distances from both radars do not differ much. The best area for comparison in Fig. 6 and 7 is SW of the C-band radars at locations corresponding to the center of images.

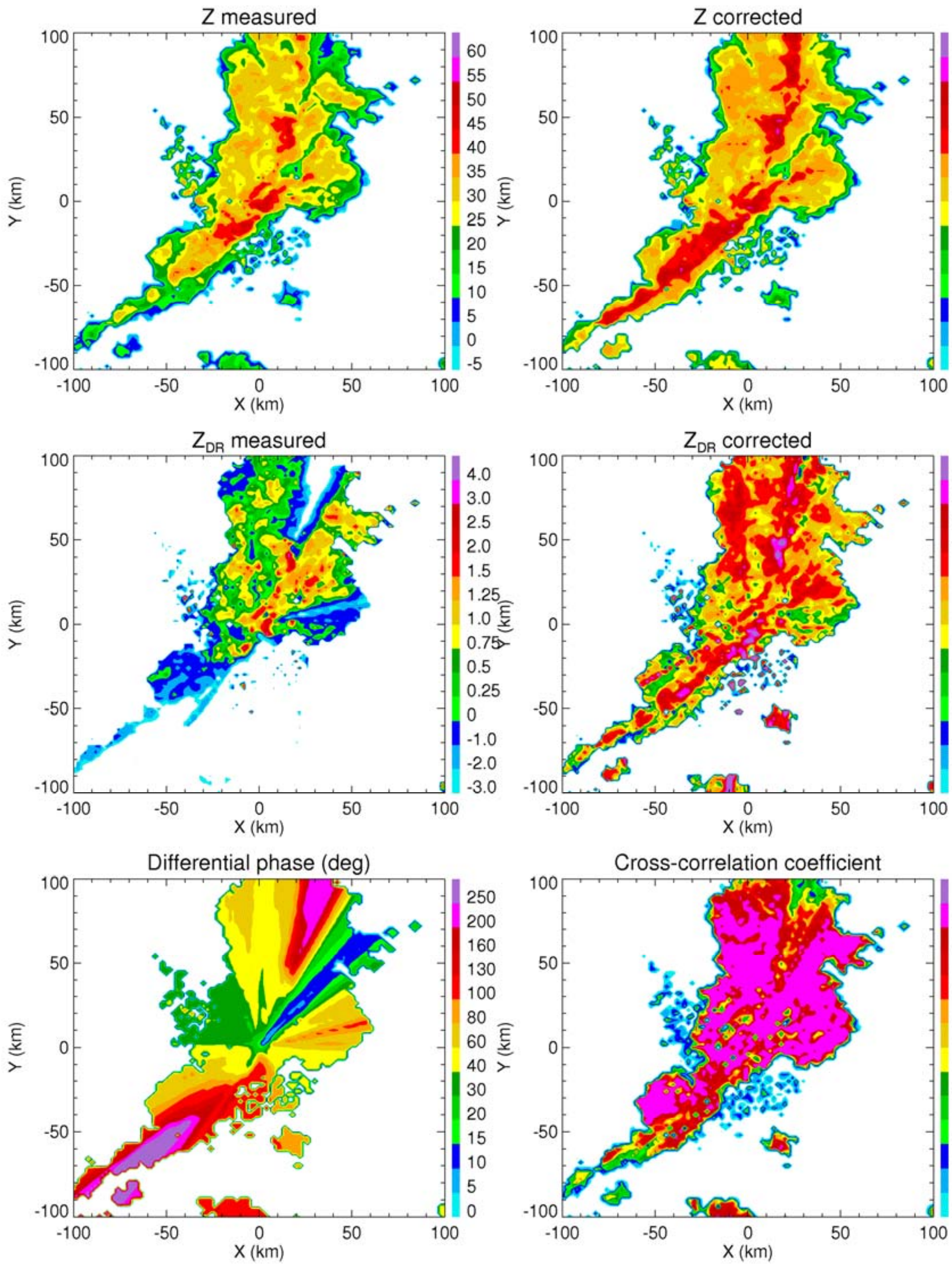

Fig. 4. Composite plot of measured and corrected Z and Z_{DR}, Φ_{DP}, and ρ_{hv} at El = 0.5° for the storm in Canada on 04/23/2007, 2030 UTC.

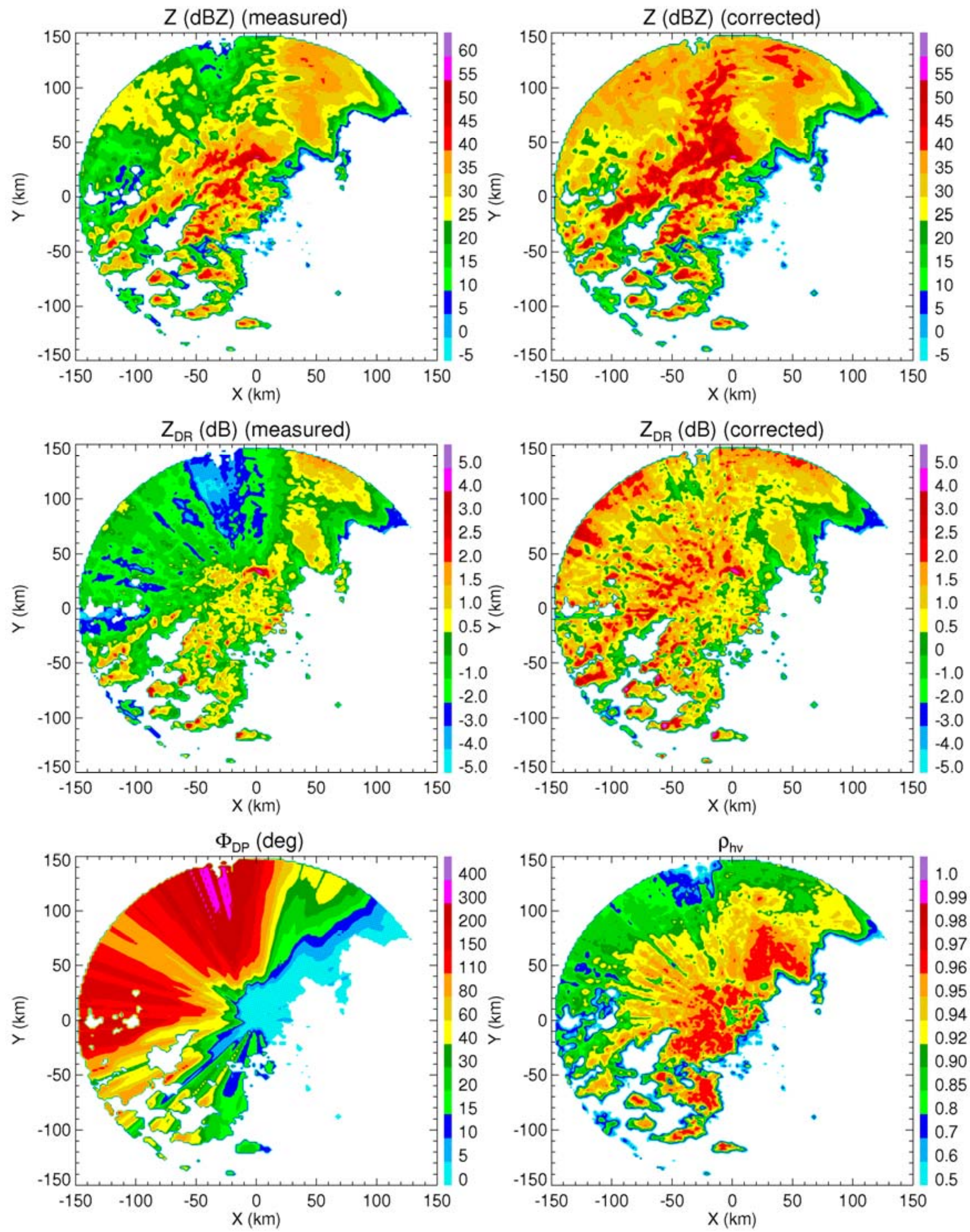

Fig. 5. Composite plot of measured and corrected Z and Z_{DR}, Φ_{DP}, and ρ_{hv} at El = 0.5° for the storm in Alabama on 11/15/2006, 1803 UTC.

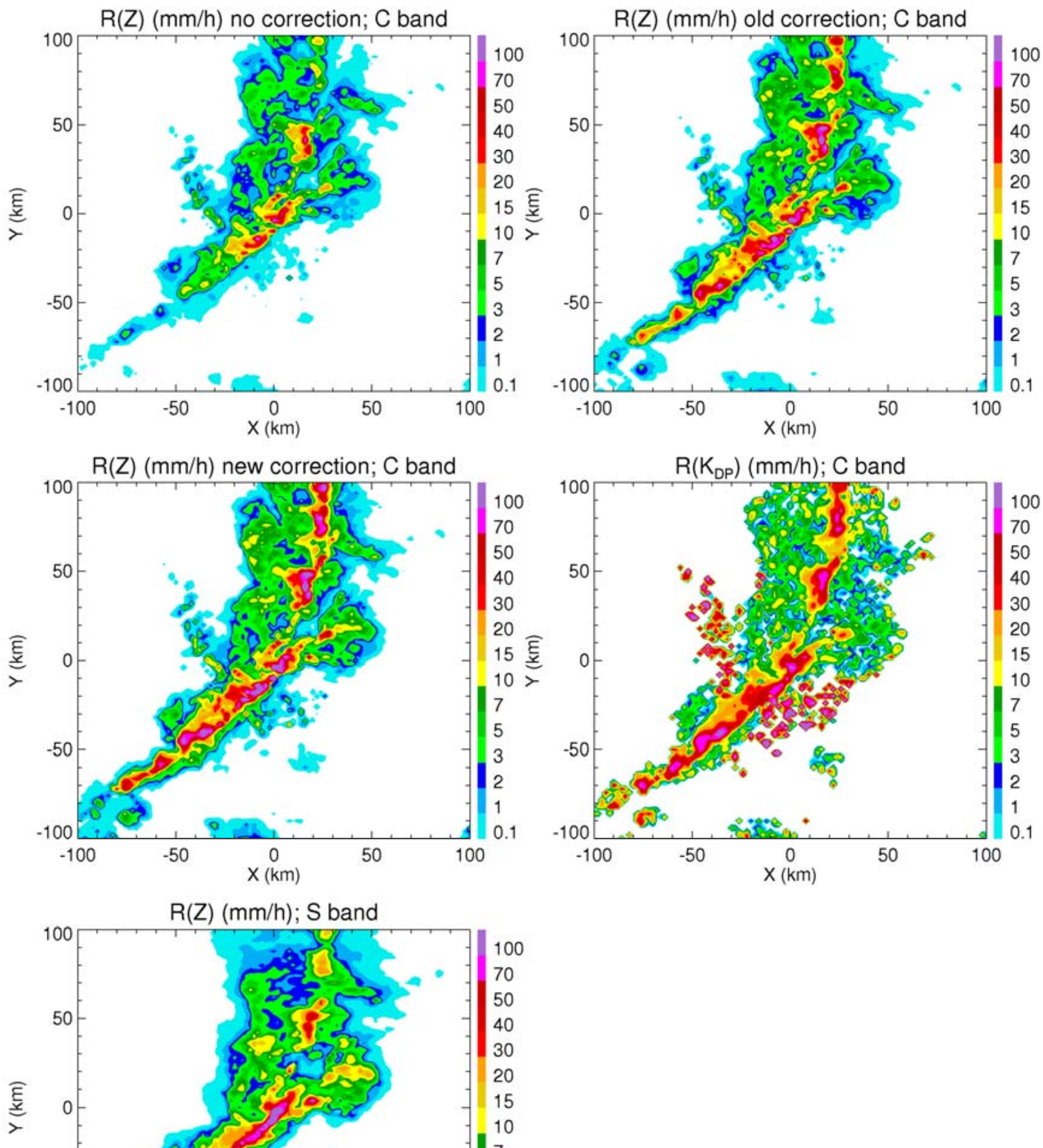

Fig. 6. Fields of rain rates retrieved from the measured and corrected Z at C band, K_{DP}, and Z at S band for the storm in Canada on 04/23/2007, 2030 UTC.

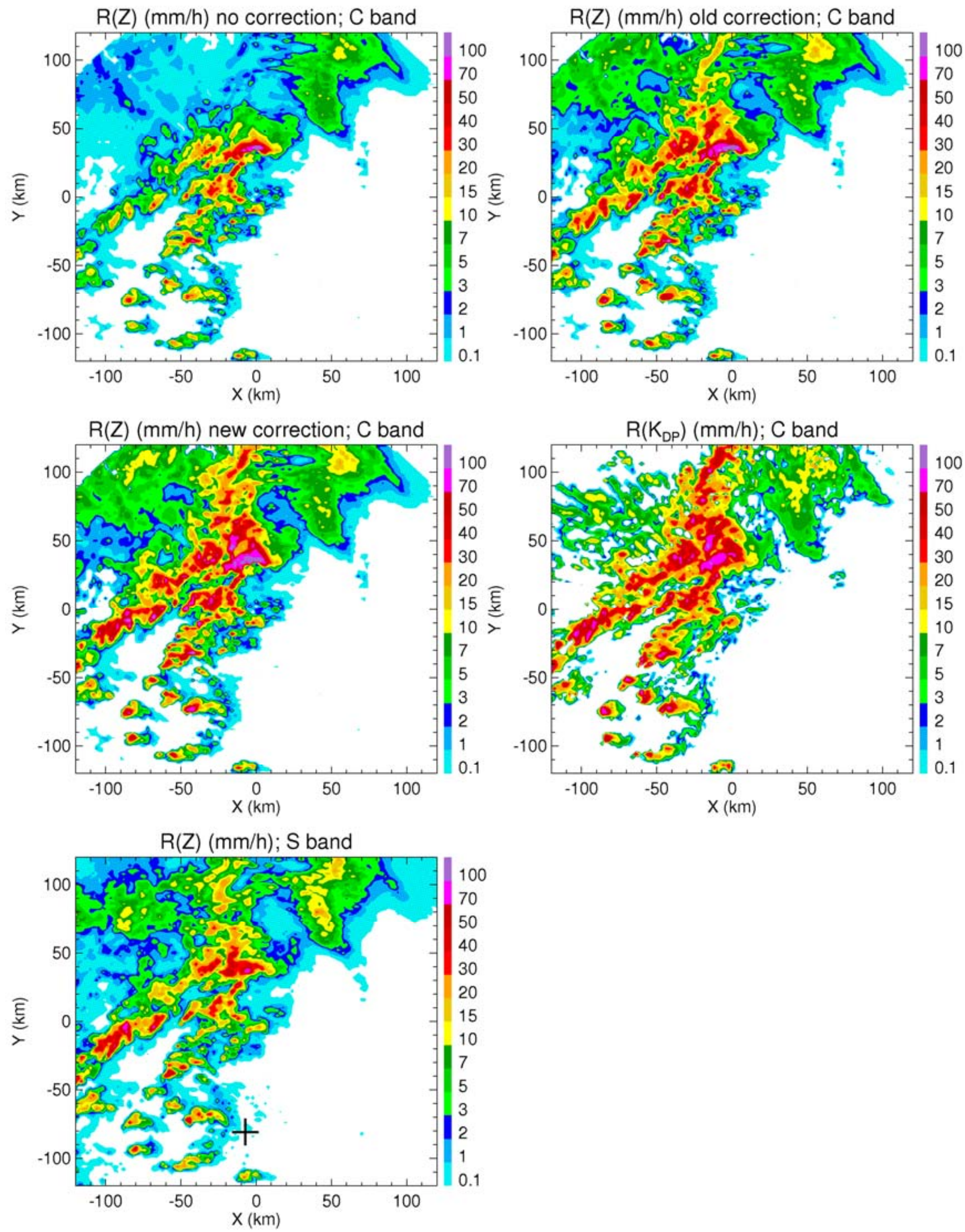

Fig. 7. Fields of rain rates retrieved from the measured and corrected Z at C band, K_{DP}, and Z at S band for the storm in Alabama on 11/15/2006, 1803 UTC.

5. SUMMARY

It is shown that relatively small segments of storms containing large raindrops and hail (“hotspots”) might be responsible for a “lion share” of attenuation / differential attenuation at C band.

A new technique for attenuation correction of Z and Z_{DR} is developed which treats “hotspots” separately from the rest of precipitation echo.

The new correction algorithm demonstrates apparent advantages over the methods which assume fixed ratios A_h/K_{DP} and A_{DP}/K_{DP} along the propagation path.

The new methodology was extensively tested and validated using C-band polarimetric measurements in Ontario and Alabama and concurrent observations with S-band WSR-88D radars.

Statistical analysis of variable coefficients α and β in “hotspots” reveals noticeable differences in microphysical processes which determine precipitation formation in Ontario and Alabama.

6. REFERENCES

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