P2.7 ATTENUATION OF RADAR SIGNAL IN MELTING HAIL AT C BAND

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1. INTRODUCTION

Anomalously high attenuation and differential attenuation at C band have been observed in recent studies (Ryzhkov et al. 2007; Tabary et al. 2008; Vulpiani et al. 2008). The questions are: (1) what is the cause of anomalous attenuation and (2) how to correct for it? It is not clear yet if it is caused by heavy rain containing large drops or melting hail, or both. High specific differential attenuation A_{DP} has often been manifested by large negative Z_{DR} in the rear side of strong convective cells. It is obviously caused by non-spherical oriented hydrometeors. Thus the key question here concerns its relation to the specific attenuation at horizontal polarization A_h; i.e., are the two correlated? Everything else being the same, large differential attenuation favors the use of Z_v rather than Z_h in regions where it is observed. In this paper, attenuation and differential attenuation at C band are estimated in storm cells suspect of having hail or rain/hail mixture. The estimates are made by comparing Z and Z_{DR} measured with a nearly collocated S band radar in Norman OK.

2. EXPERIMENTAL SETUP

The C-band radar (OU Prime) is located in Norman, Oklahoma and belongs to the University of Oklahoma. Its main characteristics are listed in Table 1. The nearly collocated S band radar is the NOAA's research version WSR-88D (designated as KOUN) that has dual polarization (Melnikov et al. 2003). Both radars operated in the so-called SHV mode, i.e. the horizontally and vertically polarized fields are transmitted and received simultaneously. Besides the difference in wavelengths, the two radars differ in beamwidth (0.5 deg for OU Prime vs ~ 1 deg for KOUN), resolution volume depth (125 m vs 250 m) and peak power (1 MW vs ~ 750 kW).

Parameter	Value
Wavelength	5.44 cm
Antenna beam width	0.5 deg
Peak transmitter power	1 MW
Pulse depth (variable) nominal	125 m
Pulse repetition time (variable) nominal	0.8 ms

TABLE 1: Characteristics of the OU Prime radar.

The radars are separated by about 6 km. This separation adds to the uncertainty of comparisons. Nonetheless, there are no closer collocated stationary dual polarization weather radars anywhere that we know of for similar comparisons.

3. MEASUREMENTS

On several occasions, polarimetric variables have been recorded quasi-simultaneously by both radars. The radars operated in surveillance scans and the beginnings of volume scans were not synchronized but the differences in time did not exceed 3 min. Cells for comparisons were chosen based on the reflectivity factor Z(S) of KOUN (11 cm wavelength) and similarity of structure observed by the two radars. In this paper, data from the cells with $Z_h > 55$ dBZ are analyzed. We have chosen two good cases for comparison of S- and C-band data: 03/10/2009 (squall line) and 03/27/2009 (strong isolated hailstorms). In the first case, hail was likely aloft but not on the ground (according to the Storm Data). In the second case, hail of 3/4" diameter was reported on the ground. Both cases reveal anomalously high attenuation and differential attenuation. For the second case the drop in Z_{DR} at C-band (down to -10 dB) was particularly larger and connected also to a larger

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negative bias in Z (deduced by comparison with S band).

Figs 1 and 2 depict the horizontal fields (PPI) and vertical cross-section (RHI), respectively, of reflectivity factor Z, differential reflectivity Z_{dr} as well as cross-correlation coefficient ρ_{hv} measured by KOUN and OU Prime on 03/10/2009 at 03:31 UTC (KOUN) and 03:32 UTC (OU Prime). The antenna elevations are 0.48° (KOUN) and 0.42° (OU Prime) for the data shown in Fig. 1. One cell in the squall line (circled) is chosen for further scrutiny. Evidence of second trip echoes is seen as elongated streaks between about 220 and 240 deg in azimuth and also at about 290 degrees. The field of differential reflectivity exhibits differential attenuation in the NW part of the storm system. Also notice the change of Z_{DR} from large positive to negative values at the location of the cell. Here also the cross correlation coefficient drops significantly. These signatures are likely associated with 5-6 mm raindrops or partially melted hailstones of similar size. Resonance scattering by large raindrops is most probably responsible for the much deeper drop of C-band ρ_{hv} in more extended areas compared to S band (Fig. 2).

Radials of reflectivity factors and polarimetric variables through one of the cells (azimuth 269.5 deg in Fig. 1) are displayed in Fig 3. The data from OU Prime radial has been shifted in range by 1 km (due to the separation of the two radars) to match the data from KOUN radar. Both measured and corrected for attenuation data are displayed. The correction assumes a linear relation between the attenuation and differential phase along the propagation path (or between A_h (A_{DP}) and specific differential phase K_{DP}). Typical coefficients of proportionality $\alpha = A_h/K_{DP}$ and $\beta = A_{DP}/K_{DP}$ are 0.06 dB/deg and 0.01 dB/deg in rain at C band. There is almost no attenuation at S band as suggested by the comparison of measured and corrected curves of Z(S) and Z_{DR}(S). At C band, this simple correction accounts only for a small portion of the observed attenuation as suggested by direct comparison with Z(S) and Z_{DR}(S).

Differential reflectivity at C band has a pronounced peak slightly ahead of the peak in reflectivity; its value of about 6 dB means that it is likely caused by abundant drops with resonant diameters near 6 mm (Zrnic et al. 2001). Note that the coincident peak in Z_{DR}(S) of about 5 dB suggests sizes in the range approaching 8 mm. Most notable is the precipitous decline in Z_{DR}(C) with range to a minimum of -5.5 dB attributable to differential attenuation. Differential reflectivity Z_{DR}(S) has a local decrease at 91 km pointing the location of a hail shaft. Thus, the reading from the Z_{DR}(S) range profile (two consecutive peaks with a valley in between that is centered on the maximum of Z(S)) is that the leading and trailing edges of the cell contain large oblate horizontally oriented hydrometeors (wet hail and/or melting hail). A hint to that is also seen in the profile of Z_{DR}(C) except the second increase is smaller and masked by differential attenuation.

Evaluation of the slopes of the range dependencies of $\Delta Z = Z(S) - Z(C)$ and $\Delta Z_{DR} = Z_{DR}(S) - Z_{DR}(C)$ indicate that maximal A_h at C band is about 2.4 dB/km and A_{DP} is about 0.7 dB/km.

Two minima in cross correlation bracketing a peak were present at S band (not shown); these are consistent with the interpretation from the Z_{DR}(S) profile. The large oblates (likely wet oriented hail) cause these decreases. At C band the cross correlation drop coincided with the increase in Z_{DR}(C) confirming the presence of resonant scatterers.

Fields of reflectivity on a conical scan (PPI) and vertical profiles (RHI) of the polarimetric variables from strong isolated hailstorms (03/27/2009) are shown in Figs. 4 and 5, respectively. The measurements have been made with the KOUN and OU Prime at 12:05 UTC (KOUN) and 12:03 UTC (OU Prime). In the PPI plot the elevation angles are 1.45° (KOUN) and 1.36° (OU Prime).

Several isolated convective cells producing hail up to 20 mm in diameter (Fig. 4) cause significant attenuation and differential attenuation at C band. Fig. 5 shows two strong convective cells centered at ranges 75 and 85 km from the KOUN radar according to the S-band reflectivity. The cell at 85 km almost entirely disappears at lower levels in the C-band data because of anomalously high attenuation.

Note that Z_{DR} has the largest negative bias at the elevation of about 1.6°. This is in agreement with the theoretical model of Ryzhkov et al. (2009) predicting that the highest A_{DP} should be expected at the height of about 2 km below the freezing level (which can be well above the ground). In the areas of rain mixed with melting hail where the impact of differential attenuation is insignificant (e.g., 70 km from the radar), Z_{DR} at C band is noticeably higher than the one at S band due to resonance scattering effects at C band caused by raindrops with diameters of about 6 mm. For similar reasons, cross-correlation coefficient ρ_{hv} at C band is lower than at S band in the areas filled with liquid or mixed-phase particles at heights below 3 – 4 km.

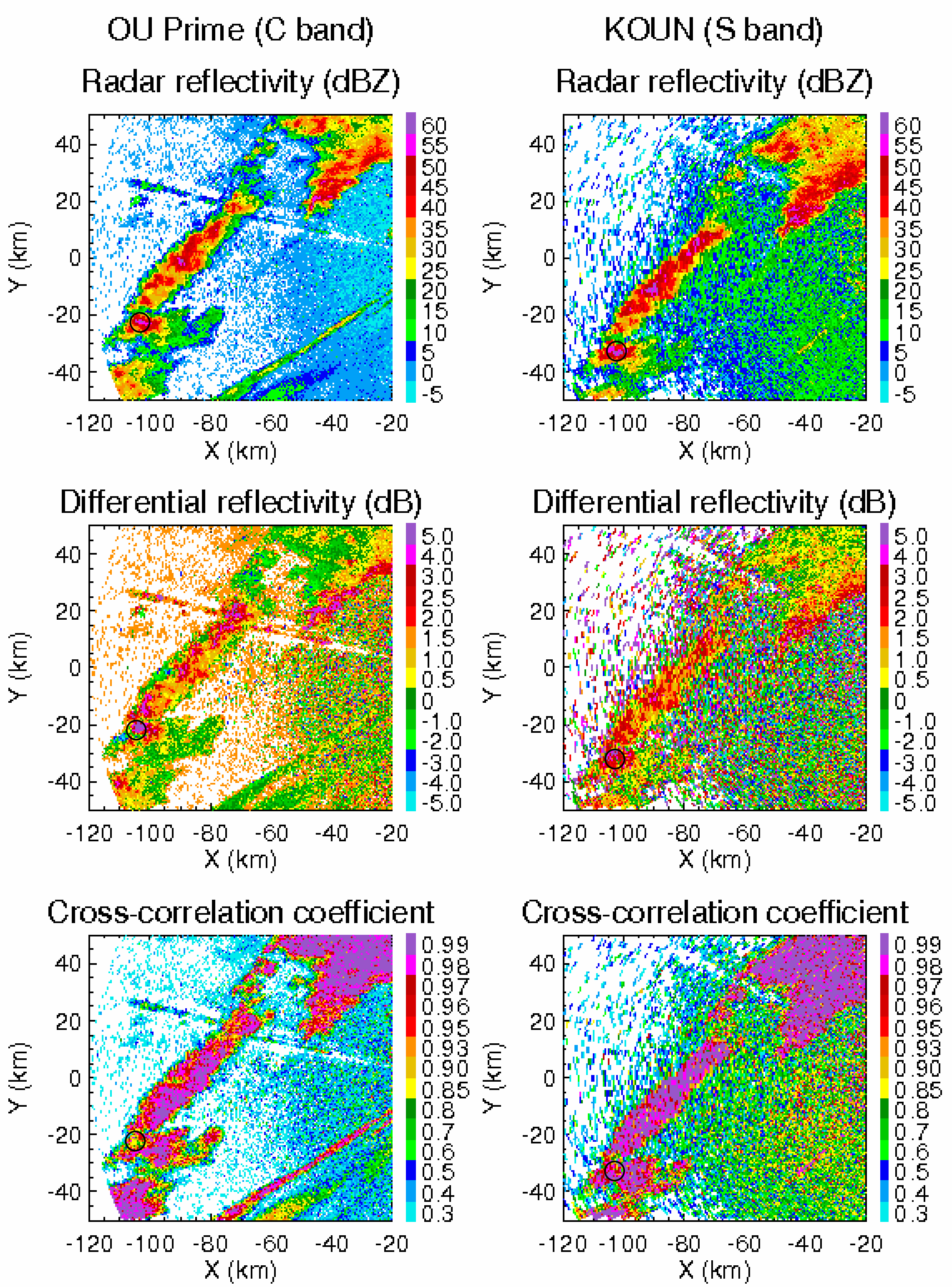

Fig. 1. Fields of measured Z(C), Z_{DR}(C), ρ_{hv}(C) at OU Prime and Z(S), Z_{DR}(S), ρ_{hv}(S) at KOUN from a conical scan at 0.42 deg (OU Prime) and 0.48 deg (KOUN) in elevations. Date was March 10, 2009, at 3:32 UTC (OU Prime) and 3:31 UTC (KOUN). The reflectivity contours in dBZ are color coded as on the bar. Contours of differential reflectivity in dB are indicated on the color bar. The circle indicates the cell for which RHI plots in Fig. 2 are presented.

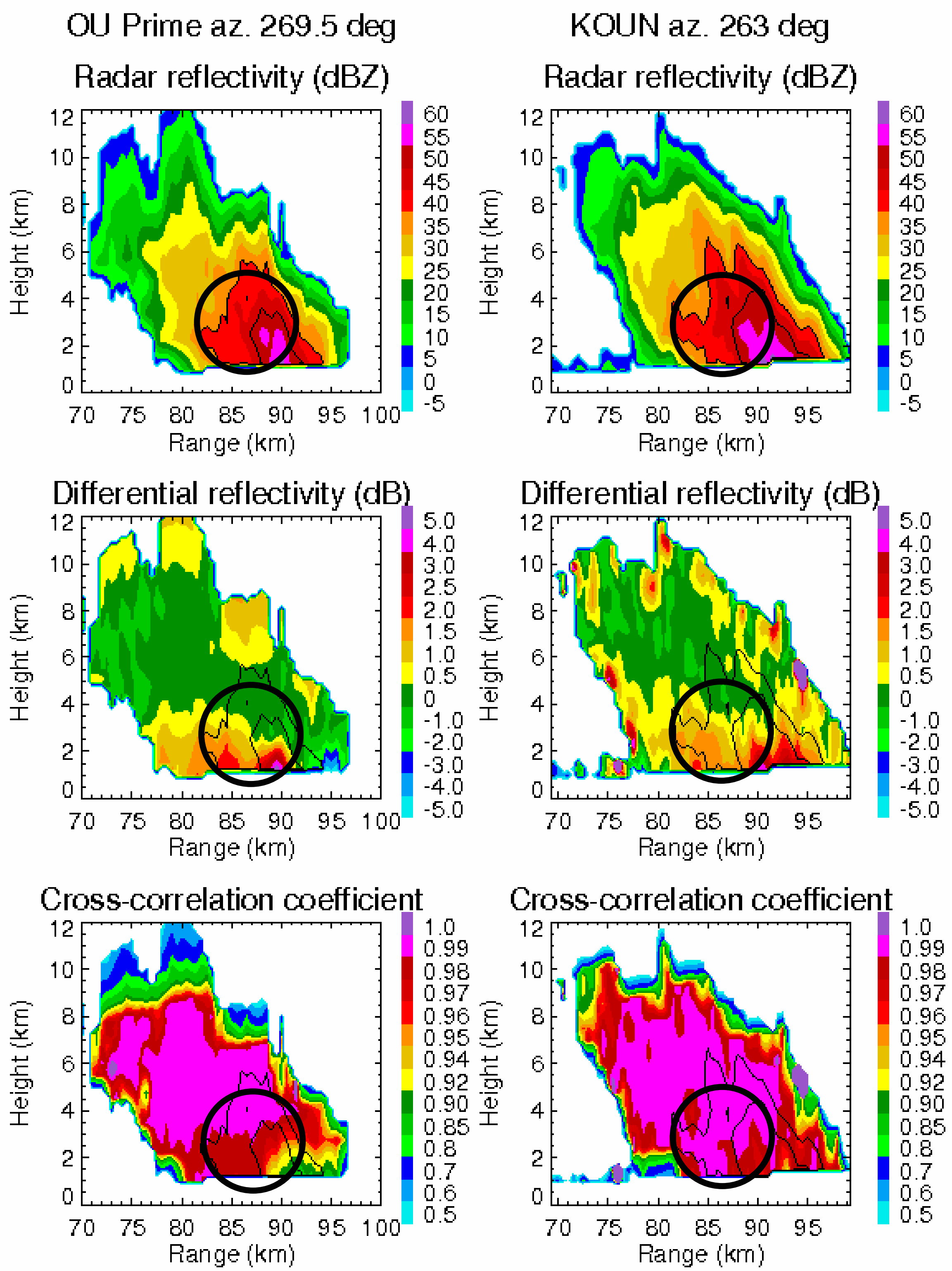

Fig. 2. Composite RHI plot of measured Z(C), Z_{DR}(C), ρ_{hv}(C) at C band and Z(S), Z_{DR}(S), ρ_{hv}(S) at S band. Date is March 10, 2009, at 3:32 UTC (C band) and 3:31 UTC (S band). The reflectivity contours in dBZ are color coded as on the bar. Contours of reflectivity Z = 40 and 50 dBZ are overlaid on the fields of Z_{DR}(C), ρ_{hv}(C). Contours of differential reflectivity in dB and of cross correlation coefficient are indicated on the color bars.

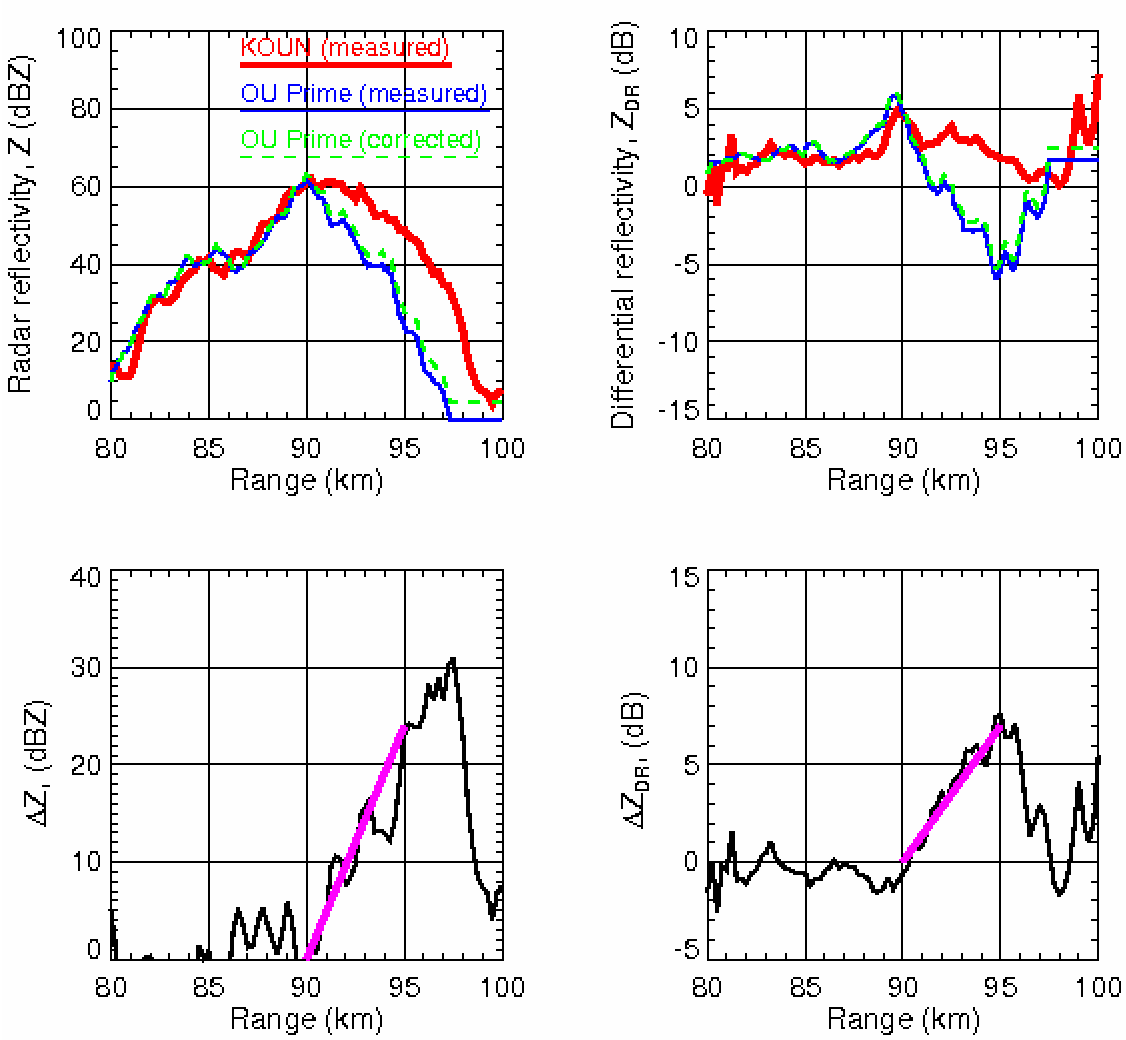

Fig. 3. Radial dependencies of Z and Z_{DR} at S (thick red curves) and C (blue curves) bands and the differences $\Delta Z = Z(S) - Z(C)$ and $\Delta Z_{DR} = Z_{DR}(S) - Z_{DR}(C)$. Dashed green curves depict corrected Z and Z_{DR} at C band if simple linear attenuation correction with $\alpha = 0.06$ dB/deg and $\beta = 0.01$ dB/deg is utilized. The thick pink straight lines in bottom panels indicate average slopes of ΔZ and ΔZ_{DR} from which the estimates of A_h and A_{DP} at C band can be obtained.

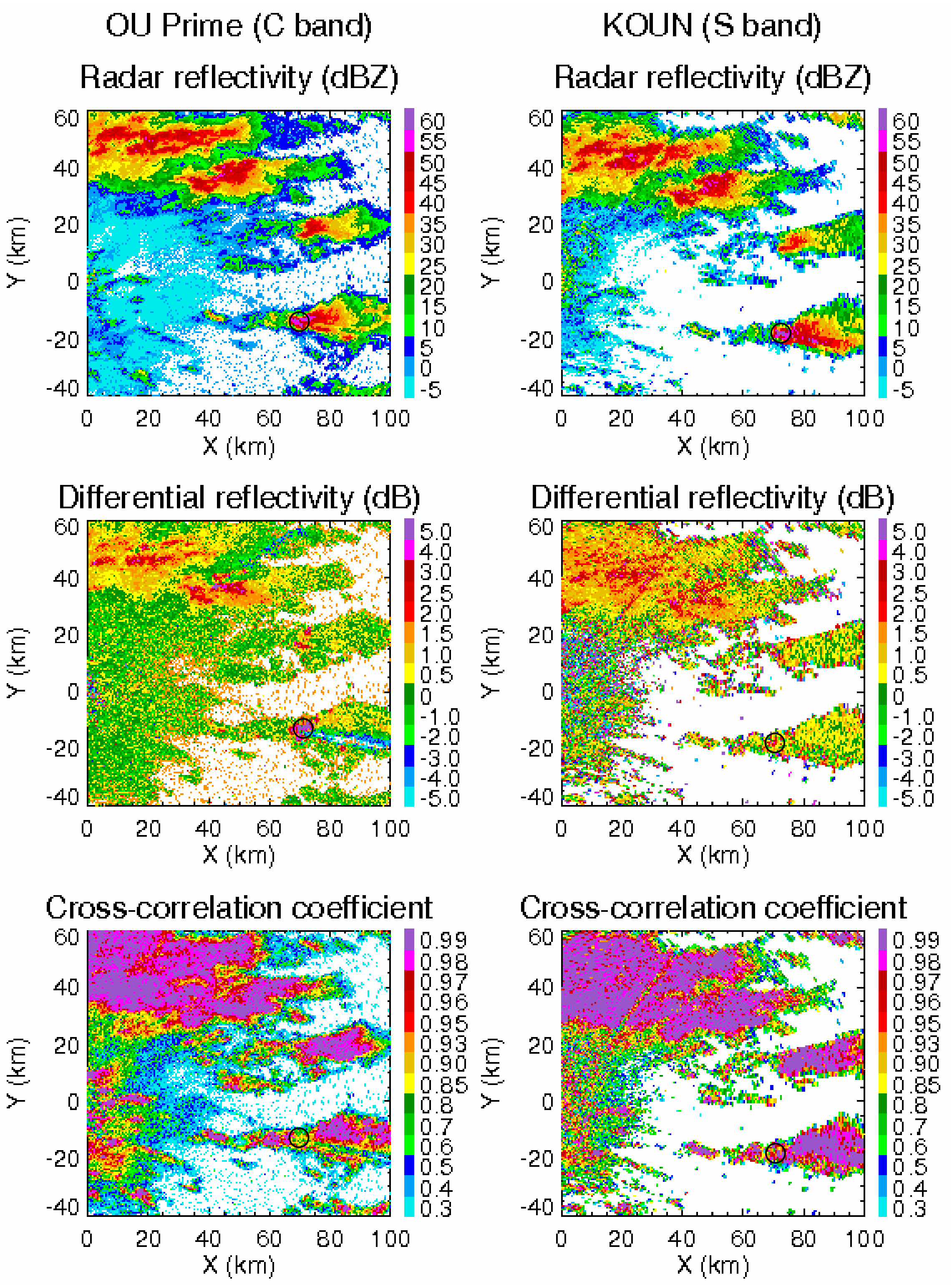

Fig. 4 Fields of measured Z(C), and Z(S), at S (KOUN) and C (OU Prime) band from a conical scan at 1.36 deg (C band) and 1.45 deg (S band) in elevations. Date was March 27, 2009, at 12:03 UTC (C band) and 12:05 UTC (S band). The reflectivity contours in dBZ are color coded as on the bar. The circle indicates the cell for which RHI plots in Fig. 5 are presented.

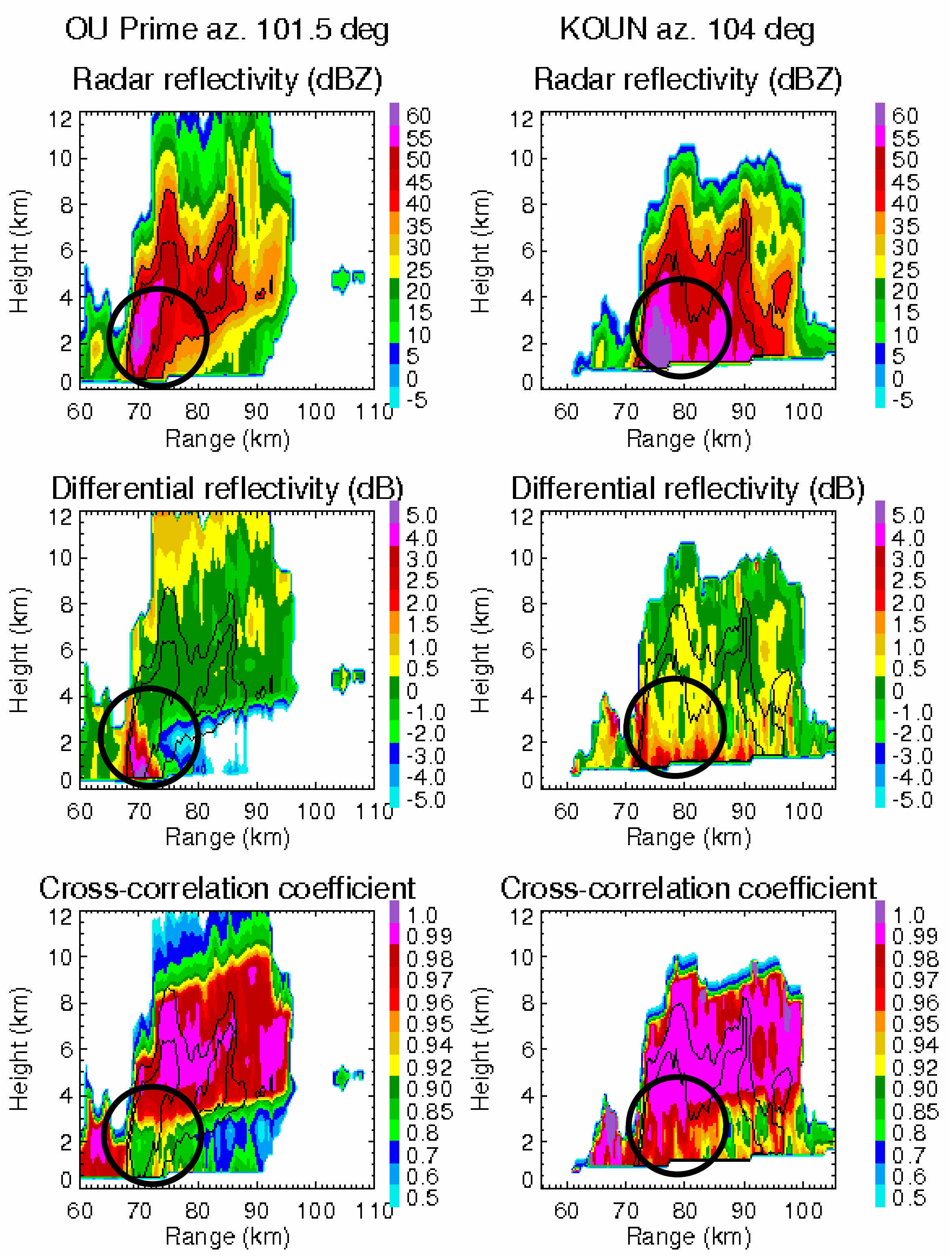

Fig. 5 Composite RHI plot of measured Z(C), Z_{DR}(C), ρ_{hv}(C) at C band and Z(S), Z_{DR}(S), ρ_{hv}(S) at S band. Date is March 27, 2009, at 12:03 UTC (C band) and 12:05 UTC (S band). The reflectivities in dBZ are color coded as on the bar and contours of reflectivity Z = 40 and 50 dBZ are overlaid on the fields of Z_{DR}(C), ρ_{hv}(C). Contours of differential reflectivity in dB and of cross correlation coefficient are indicated on the color bars.

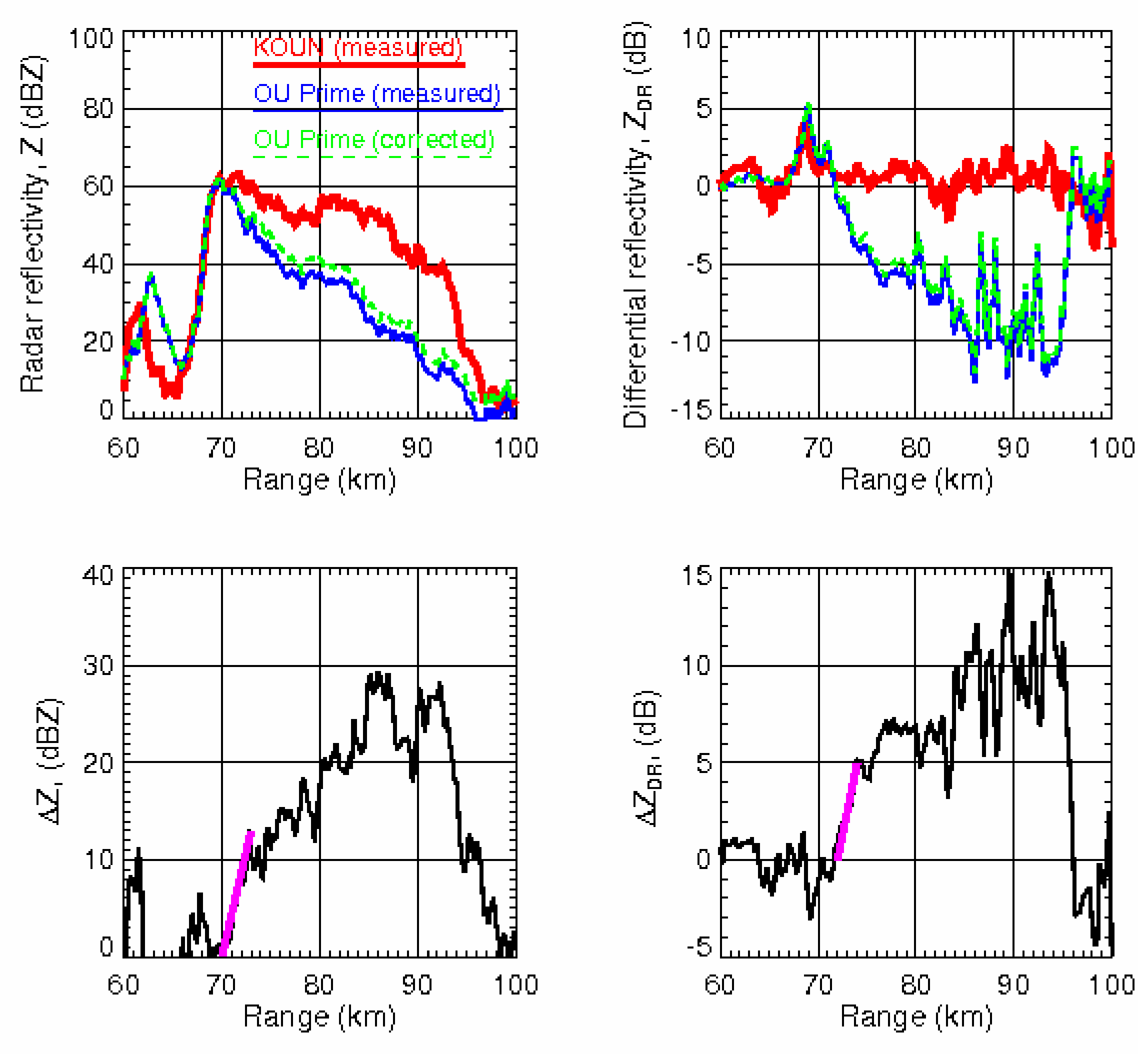

Fig. 6. Radial dependencies of Z and Z_{DR} at S (thick red curves) and C (blue curves) bands and the differences $\Delta Z = Z(S) - Z(C)$ and $\Delta Z_{DR} = Z_{DR}(S) - Z_{DR}(C)$. Dashed green curves depict corrected Z and Z_{DR} at C band if simple linear attenuation correction with $\alpha = 0.06$ dB/deg and $\beta = 0.01$ dB/deg is utilized. The thick pink straight lines in bottom panels indicate average slopes of ΔZ and ΔZ_{DR} from which the estimates of A_h and A_{DP} at C band can be obtained.

From the slopes of the range dependencies of $\Delta Z = Z(S) - Z(C)$ and $\Delta Z_{DR} = Z_{DR}(S) - Z_{DR}(C)$ we find that maximal A_h at C band is about 2.17 dB/km and A_{DP} exceeds 1.25 dB/km. These estimates are generally consistent with theoretical predictions of Ryzhkov et al. (2009) for maximal hail size of 20 mm at the surface.

5. DISCUSSION

This is the first time S and C-band polarimetric radar observations are directly compared. There are significant differences in the S and C-band polarimetric signatures in strong convective storms. Most notable are the differences in reflectivity factors in the rear side of the convective cells. Differential reflectivities at C band are higher in the areas not affected by differential attenuation than differential reflectivities at S band while the cross correlation coefficients at C band drop much more than the cross correlation coefficients at S band. The main reasons are the resonance scattering effects associated with large raindrops at C band.

Attenuation and the differential attenuation are much higher in storms containing hail (at the ground and aloft) compared to pure rain. According to theoretical studies, this is due to direct contributions to A_h and A_{dp} of melting hailstones in the size range between 8 and 20 mm and due to the enhancement in concentration of large raindrops originating from completely melted hail. The direct contribution from melting hail is dominant at higher altitudes, whereas the contribution from raindrops is overwhelming at lower altitudes where the concentration and size of melting hailstones decreases. The experimentally estimated maximal A_h and A_{dp} in the two cases analyzed (03/10/2009, 03/27/2009) are about 2.4 and 2.17 dB/km and 0.7 - 1.25 dB/km, respectively. These are significantly higher than the maximal values expected from direct observations and simulations based on disdrometer measurements in Oklahoma. Quite often, maximal differential attenuation (and possibly total attenuation) is observed at higher elevation angles in full agreement with theory (as RHI for 03/27/2009 case demonstrates).

According to our results common techniques for attenuation correction in rain (e.g. Bringi et al. 1990, 2001) dramatically underestimate attenuation and differential attenuation in strong hail-bearing storms. Therefore a new approach should be investigated.

6. REFERENCES

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