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ON THE ROLE OF X-BAND RADAR IN EXTENDING LONGER-WAVELENGTH RADAR POLARIMETRIC RETRIEVALS TO LIGHTER RAINS

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1. INTRODUCTION

Polarimetric radar approaches for retrievals of rainfall parameters have been in use for more than 20 years. These approaches were first developed and tested with longer wavelength radars operating at S (λ ~11 cm) and C (λ ~5 cm) bands because these band frequencies are traditionally used for quantitative precipitation estimations (QPE). Meteorological X-band (λ ~3 cm) radars have been traditionally limited in their applicability for QPE due to relatively high attenuation (differential attenuation) rates of reflectivity, Z_{eh}, (differential reflectivity, Z_{DR}) in rain. In the last 5 years or so, however, several polarimetric X-band radars have been introduced worldwide (e.g., Iwanami, et al. 2001, Martner, et al. 2001, Wurman 2001, Gosset and Cazenave 2003).

Special polarimetric procedures have been developed to correct radar power measurements for effects of attenuation and differential attenuation (e.g., Matrosov et al. 2002, Anagnostou et al. 2004). These correction procedures greatly mitigate signal attenuation issues and significantly extend the usable range of X-band radar QPE measurements. Total signal loss, however, can occur at longer ranges in heavy rain, thus making X-band radars effective for QPE at generally shorter ranges (~50 km or so) compared to S-band radars (~250 km or so).

Aside form this important range limitation, X-band polarimetry offers some important advantages over longer wavelength polarimetry at shorter ranges and lighter rainfall rates. The main advantage is a significantly stronger differential phase shift on propagation which is proportional to the radar frequency (for Rayleigh scattering). This allows the use of specific differential phase shift (K_{DP}) based rainfall estimators for lighter rainfall rates when measured with X-band radars than when measured with longer wavelength radars. These estimators have important advantages over the power-based estimators (Zrnic and Ryzhkov 1996) due to their modest dependence on details of drop size distributions (DSD) and independence of the absolute radar calibration.

This study presents some illustrations of the comparative use of S- and X-band radars for measurements of light to moderate rains that contribute a significant fraction of annual accumulations in many parts of the world.

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2. THEORETICAL CONSIDERATIONS

For Rayleigh scattering, Z_{DR} values do not depend on the radar wavelength and K_{DP} values are proportional to the reciprocal of the wavelength. Although rain drops are still generally small compared to the X-band wavelengths, there are already some non-Rayleigh effects that might show up in measurements. To assess the magnitude of these effects, Figure 1 shows the dependence of the individual drop ratio of differential reflectivity (r_{ZDR}) and the wavelength scaled ratio of specific differential phase (r_{KDP}) as functions of the equal-volume spherical drop diameter (D). r_{ZDR} and r_{KDP} are defined as:

$$r_{ZDR}=[\sigma_{hx}(D)/\sigma_{vx}(D)][\sigma_{hs}(D)/\sigma_{vs}(D)]^{-1} \quad (1)$$

$$r_{KDP}=\{\lambda^2_x \mathrm{Re}[f_{hx}(D)-f_{vx}(D)]\}\{\lambda^2_s \mathrm{Re}[f_{hs}(D)-f_{vs}(D)]\}^{-1}, \quad (2)$$

where σ_{hx}, σ_{vx}, σ_{hs}, σ_{vs} are the horizontal (h) and vertical (v) polarization backscatter cross-sections at S-band (λ_s=11 cm) and X-band (λ_x=3.2 cm) wavelengths, and f_{hx}, f_{vx}, f_{hs}, f_{vs} are the forward scattering amplitudes at these polarizations and wavelengths. The drops were modeled as oblate spheroids with their symmetry axes oriented vertically.

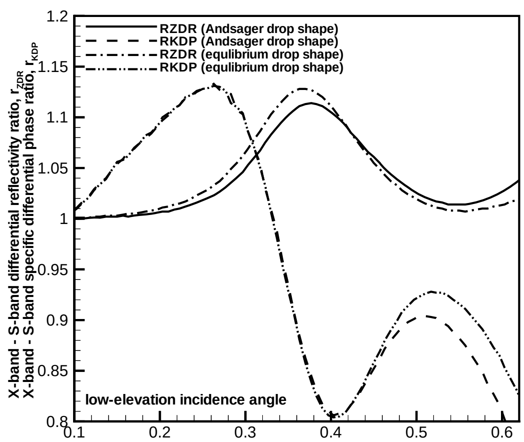

FIG.1. r_{ZDR} and r_{KDP} as functions of drop size.

Calculations of r_{ZDR} and r_{KDP} were performed for the equilibrium drop aspect ratio (a/b):

$$a/b = 1.031 - 0.62\,D \quad (D>0.05 \text{ cm}), \quad (3)$$

and the aspect ratio suggested by Andsager et al. (1999):

$$a/b = 1.012 - 0.144D - 1.03D^2 \quad (D \text{ in cm}) \qquad (4)$$

If scattering were strictly of the Rayleigh type, $r_{ZDR} = r_{KDP}=1$. The deviations from the Rayleigh-type scattering at X-band result in a slightly greater increase of X-band K_{DP} values (compared to S-band) for drops with D < 0.35 cm than predicted by simply scaling wavelengths. Calculations using experimental DSDs for light-to-moderate rains (2 $mmh^{-1} < R < 20$ mmh^{-1}) show that, for these particular wavelengths (λ_s=11 cm) and X-band (λ_s=3.2 cm), X-band K_{DP} is a factor of about 3.75 greater than S-band K_{DP} (with little dependence on R or on drop shape-size relations) while simple Rayleigh wavelength scaling predicts a factor of 3.45. It is expected that a higher differential phase accumulation rate at X-band would provide appreciable and thus usable K_{DP} values in rains when S-band phase measurements are too noisy to provide K_{DP} estimates. In heavier rains when both S-band and X-band K_{DP} values are available, smaller integration paths can be used at X-band to accumulate the same phase difference thus providing potentially better spatial resolution for K_{DP}-based rainfall estimators.

It can also be seen from Fig.1 that drops with 0.25 cm < D < 0.5 cm provide higher differential reflectivity at X-band compared to S-band. It can result in few tenths of 1 dB higher X-band Z_{DR} values. Modeling with experimental DSDs indicates that the X-band Z_{DR} increase over S-band Z_{DR} generally exceeds 0.2 dB (a typical uncertainty of Z_{DR} measurements) for median drop diameters D_0> 0.2 cm.

3. EXPERIMENTAL EXAMPLES

During a two month period (16 May 2004 – 15 July 2004), the NOAA Environmental Technology Laboratory (ETL) X-band radar (λ_x=3.2 cm) and the Colorado State University (CSU) CHILL radar (λ_s=11 cm) were simultaneously observing rainfall in the Northeastern Colorado as part of the Global Precipitation Mission (GPM) – Ground Validation (GV) pilot study. Although the radars were not collocated, CHILL was covering the NOAA/ETL X-band radar scan area, so both X- and S-band radar polarimetric data were available in a sector (0-39 km radius) between 60° and 180° azimuthal directions centered at 105° W and 40.1° N. Two ground sites equipped with rain gauges and disdrometers were available for verification of radar retrievals.

A relatively light stratiform rain observed by both radars on 21 June provided an opportunity to assess the utility of the X-band differential phase shift approach in situations when S-band differential phase data are too noisy to use this approach. Figure 2 shows horizontal reflectivity time series of both radars (X-band data were corrected for attenuation) over the Boulder Atmospheric Observatory (BAO) ground-based site during this event. The rainfall rates, R, calculated from DSDs recorded by the impact Joss-Waldvogel disdrometer are also shown in this figure.

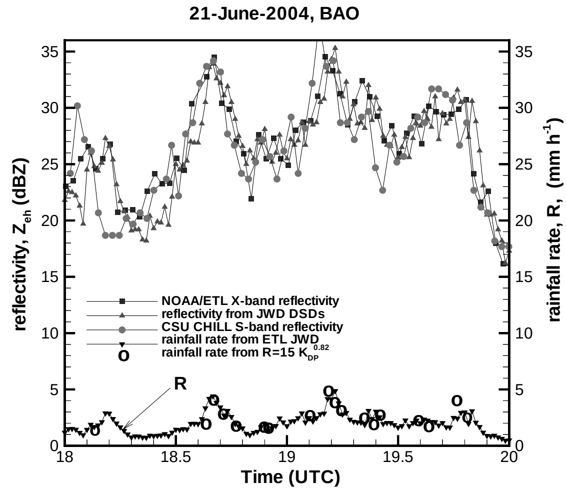

FIG.2. Reflectivity and rainfall rate time series at BAO.

Given the different altitudes of the centers of the radar beams (120 m AGL for the NOAA/ETL X-band and 300 m AGL for CHILL), there is a good agreement among reflectivity data. Non-Rayleigh effects on X-band reflectivities for Z_{eh}<40 dBZ do not exceed 1 dB which is close to a typical calibration uncertainty.

Figure 3 shows K_{DP} values over the BAO site calculated from the differential phase measurements at X and S-bands. S-band K_{DP} data are unusable and just represent the noisy phase measurements. X-band K_{DP} data exhibit much less noisiness, and they are stably positive above 0.1 deg km^{-1} for the periods when rainfall rate exceeds about 2.5 mm h^{-1} (i.e., between 18.6 and 18.7, 19.15 and 19.25, 19.7 and 19.8 in decimal UTC).

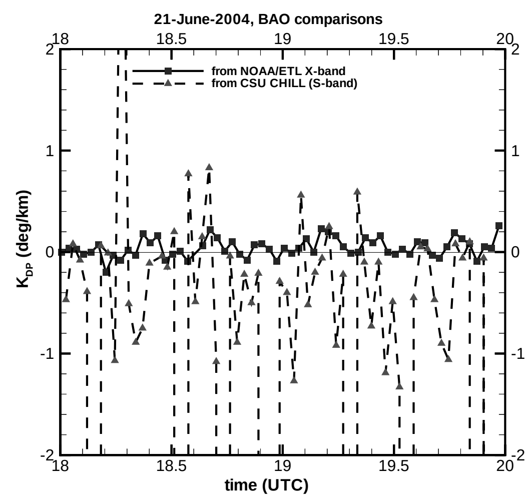

FIG.3. X and S-band K_{DP} time series at BAO. 21-Jun-04.

It was found that typically for GPM pilot data, X-band K_{DP} values were stably higher than about 0.1 deg km^{-1} and usable when reflectivities were higher than about 26-27 dBZ. For S-band, usable K_{DP} data did not become available until reflectivity levels reach ~35-40 dBZ.

In the ETL routine retrievals during the GPM pilot experiment, polarimetric rainfall rate estimates are calculated when two conditions are satisfied: i) K_{DP} >0.07 deg km^{-1}, and ii) Z_{eh} > 27dBZ (Matrosov et al. 2005). A K_{DP} –based polarimetric estimator uses the following K_{DP}–R relation:

$$R = 15\, K_{DP}^{\;0.82} \qquad (5)$$

Estimates from this relation (when available) are also shown in Fig.2.

When at least one of the above-mentioned conditions is not satisfied, the X-band radar derived rainfall rates are estimated using the generic NEXRAD *Z-R* relation (Z_{eh}=300$R^{1.4}$). Figure 4 shows the time series of the rainfall accumulation over BAO sites calculated using the radar data compared to the high-resolution (0.01") gauge measurements.

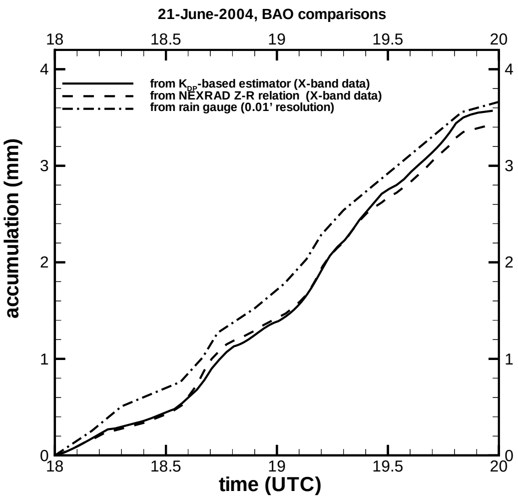

FIG.4. Time series of rain accumulation at BAO. 21-Jun-04.

The results of the NEXRAD *Z-R* relation algorithm applied to CHILL data (not shown) practically coincided with the X-band *Z-R* based estimates of accumulation. CHILL polarimetric estimates using the blended S-band algorithm (Cifelli et al. 2002) significantly underestimated the observed rain accumulation in part due to noisiness in differential phase data. Though the polarimetric estimates from X-band data were available only for about 20% of the total duration of this light rain storm event (mostly corresponding to the periods with R > 2.5 mm h^{-1}), they improved agreement of radar retrievals with the gauge data. Based on more extensive use of X-band only data (Matrosov et al. 2005), it was established that the use of K_{DP} –R relations (when polarimetric radar estimates are available) instead of mean *Z-R* relations diminishes the standard deviation between radar and rain gauge accumulation data on average by a factor of 1.5 or so.

X-band Z_{DR} measurements at BAO site during the periods of higher rainfall rates mentioned above (i.e., between 18.6 and 18.7, 19.15 and 19.25, 19.7 and 19.8 in decimal UTC) were on average higher than those at S-band by about 0.2 dB. This bias could be, in part, due to non-Rayleigh effects discussed in section 2.

4. CONCLUSIONS

X-band differential phase shift measurements typically become meaningful at rainfall rates as low as 2-3mmh^{-1} which approximately corresponds to reflectivities of 26-29 dBZ. This allows calculating K_{DP} values for such relatively light rains. Applying mean K_{DP} –R relations instead of mean *Z-R* relations generally results in better estimates of rainfall accumulation. At S-band, propagation differential phase effects are a factor of about 3.7 weaker than at X-band, and the quantitative use of K_{DP} data is generally not possible for rainfall rates lighter than ~7-10 mm h^{-1} (or reflectivities less than ~ 35-38 dBZ). At longer ranges, however, due to substantial attenuation in rain, X-band measurements can be completely extinguished by the cells of heavy rain. This limits the use of X-band radar rainfall retrievals to situations with light-to-moderate rains (and to shorter ranges if cells of heavy rain are present) when the polarimetric schemes for correcting attenuation and differential attenuation effects can be used. Ideally, collocated dual-wavelength radar measurements of rainfall can combine the advantages of both bands, i.e, the availability of polaimetric differential phase estimates for lighter rainfalls at X-band and longer range coverage with negligible attenuation at S-band.

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