Rainfall retrieval from polarimetric X-band radar measurements

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1 Introduction

Dual polarization radars have shown considerable improvement of quantitative estimation of rainfall rate and raindrop size distribution (DSD) parameters. Most studies have been done with S and C-band radars and only a few studies with higher X-band weather radars. X-band radars have the advantages of lower cost and higher differential phase shift but with higher attenuation too. Furthermore, there is still potential for further improvement of the accuracy of the rain parameters obtained from polarimetric estimators. This work presents development and validation of polarimetric estimators of rainfall at X-band using a normalization method.

2 Measurements

The data used in the work were collected during autumn 2005-winter 2006 in the Athens urban area using a mobile Doppler dual polarization radar operating at X-band, a 2D video disdrometer and tipping bucket rain gauges for radar calibration and validation purposes. The radar was operated at National Observatory site at an altitude of 500m and the disdrometer with rain gauges was deployed at an altitude of 150 m at a distance 10 km away from the radar. Radar observations include horizontal reflectivity Z_h, differential reflectivity Z_{dr} and differential phase Φ_{dp}. PPI scans at low elevation angle (<=1.5^o) were performed as well as RHI scans above the in-situ sensors in order to estimate any altitude dependence of radar rainfall estimates. The disdrometer data was used for the analysis of DSD, shape (axis ratio) and orientation (canting) of rain droplets, and the theoretical estimation (simulation) of polarimetric radar products. The observed rain intensities ranged from light stratiform events to heavy convective storms.

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3 Data processing

3.1 Radar attenuation correction

At X-band frequencies attenuation of radar signal by rain can be quite significant. The attenuation correction method used is ZPHI (Testud et al. 2000), which is based on Φ_{dp} measurements, combined with a Φ_{dp}-Z_{dr} constraint self consistent method (Bringi et al. 2001). This method was applied to separate rain cells defined by correlation between polarization channels higher than 0.8. However, in the case of Z_{dr} constraint the difference of Z_{dr} from the beginning of the rain cell was used in the fitting procedure instead of the absolute value of Z_{dr} (Bringi et al. 2001; Park et al. 2005a) to make the method fully independent of calibration offsets.

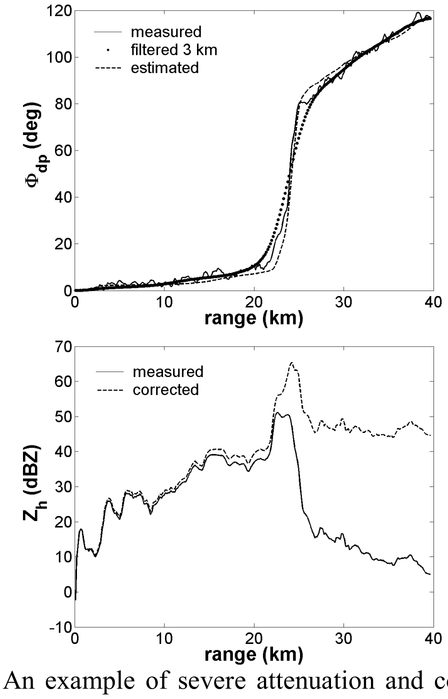

Fig. 1. An example of severe attenuation and correction of radar horizontal reflectivity Z_h.

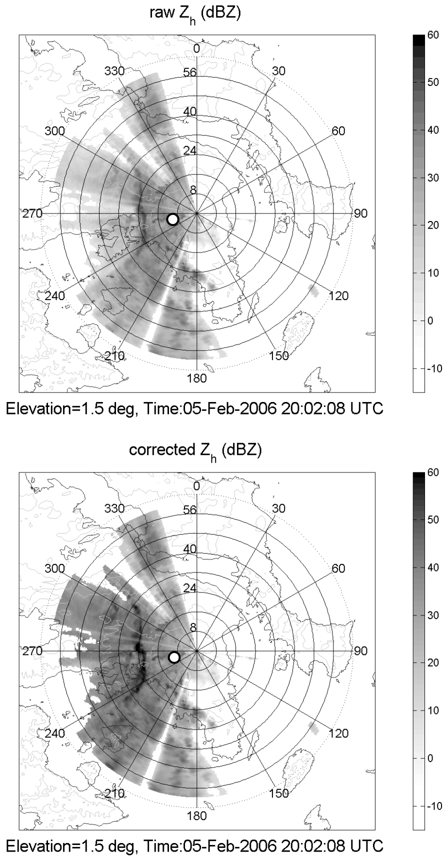

Fig. 2. PPI images of Z_h before and after attenuation correction corresponding to Fig. 1. The shoreline and disdrometer site (white dot) are also shown.

Figures 1and 2 give an example of severe signal attenuation due to a front of very heavy rain approaching from the west. The corrected Z_h is almost steady behind the front, which may be expected, and there is spatial variability similar with the variability ahead of the front where attenuation is small.

3.2 Rain parameters estimation

Various polarimetric estimators of rainfall parameters at X-band presented in the literature were evaluated using the current dataset. These estimators, which combine Z_h, Z_{dr} and specific differential phase K_{dp}, include relations from Matrosov et al. (2002) and Park et al. (2005b). The classic Z-R estimator with steady coefficients corresponding to average values for the full radar dataset was also evaluated.

Assuming that a normalized Gamma distribution is valid for DSD modeling the precipitation parameters are proportional to the intercept parameter N_w. Thus, it may be expected that normalization by N_w will lead to reduced error of rainfall estimation. Figure 3 shows the results of this normalization using T-matrix scattering simulation of Z_h using disdrometer DSD data. N_w is estimated by fitting the Gamma distribution or from moments of the measured DSD. The nonlinear behavior (variable slope) observed in Fig. 3 is due to Mie scattering effects (Ulbrich 1988). Thus, it may be possible that a higher order polynomial can be used to improve rainfall estimation.

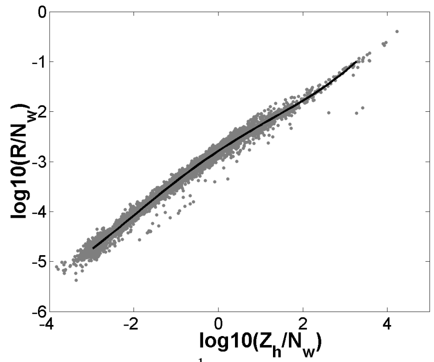

Fig. 3. Rainfall R(mm h^{-1}) and simulated reflectivity Z_h ($mm^6\ m^{-3}$) normalized by the measured intercept parameter N_w ($mm^{-1}\ m^{-3}$) for the full disdrometer dataset. A 4th order polynomial is fitted to the data.

The polarimetric estimators of N_w and median volume diameter D_0 used by Park et al. (2005b) were found to give biased estimates compared to direct estimates from disdrometer DSD. Using T-matrix scattering simulations, which included a Fisher distribution with a 15^o standard deviation for canting angle and a broader range of DSD parameters according to disdrometer measurements, modified estimators were obtained at X-band:

$$\log_{10}(N_w)=2.48Z_h^{0.099}Z_{dr}^{(-0.067\beta^{-1.15})}\ \ (mm^{-1}\ m^{-3}) \qquad (1)$$

$$D_0=0.75Z_h^{0.057}Z_{dr}^{(0.03\beta^{-1.22})}\ \ (mm), \qquad (2)$$

where β is the effective slope of the dependence of droplets axis on their diameter:

$$\beta=5.69(K_{dp}/Z_h)^{0.41}(Z_{dr}-1)^{0.58}\ \ (mm^{-1}) \qquad (3)$$

and Z_h and Z_{dr} have linear units.

Using the N_w from Eq. (1) different variants of the N_w normalization method for rainfall rate R estimation:

$$R=cN_w(Z_h/N_w)^d \qquad (4)$$

were evaluated. These variants include constant ($c=1.305x10^{-3}$, $d=0.58$) or variable coefficients c and d in Eq. (4) or a higher order polynomial of $\log_{10}(R/N_w)$ vs. $\log_{10}(Z/N_w)$ according to Fig. 3. The variability of c and d coefficients was prescribed as a function of K_{dp}/N_w based on current simulations or using their dependence on β parameter presented by Anagnostou et al. (2004).

4 Results

Figures 4 and 5 show time series of estimated rain parameters during a stratiform like (light widespread rain) event. NE and NB are the average normalized (with mean value) total error and bias, respectively, of radar estimates for rainfall rate more than 0.1 mm h^{-1}. It can be seen that the classic and Matrosov's estimators overestimate significantly the rain around 1600 UTC, while Park's estimator significantly overestimates rain during most of the event time period and clearly it is not fitted to the current data set. N_w normalization gives quite accurate results with very small bias closely following short rain variations. N_w and D_0 are also well estimated by Eqs. (1) and (2) which are adjusted to the disdrometer data set.

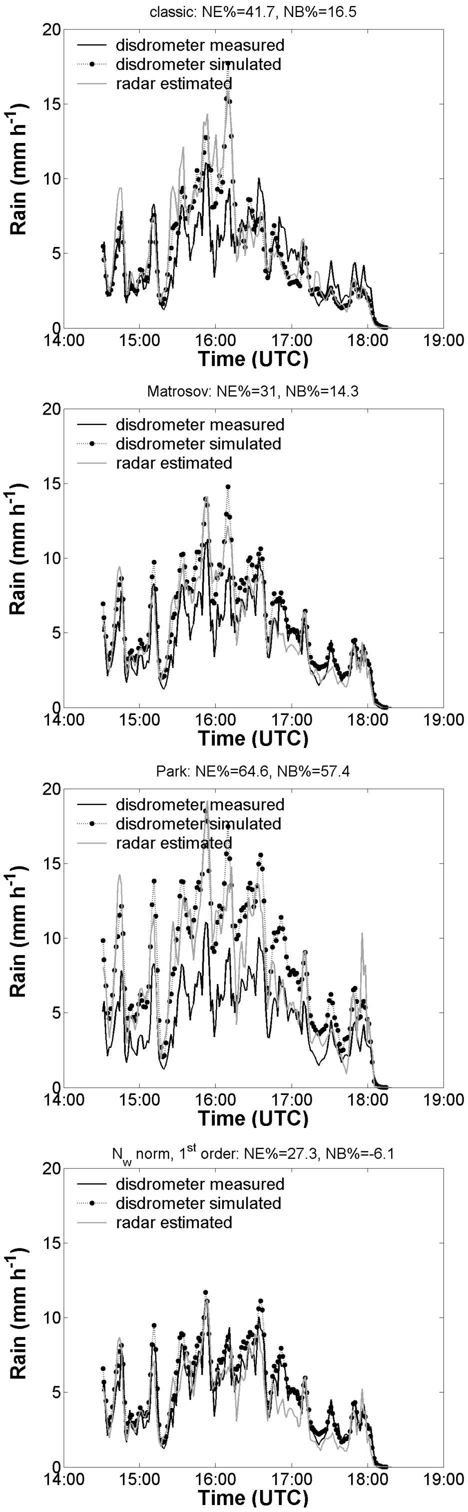

Fig. 4. Time series of disdrometer measured rainfall and estimators from disdrometer simulated and radar measured Z_h, K_{dp}, and Z_{dr} during a stratiform like rain event (17/11/2005).

Figure 6 shows scatter plots of rainfall estimation including all rain events that were observed from both the radar and the disdrometer. The classic estimator has a good behavior on average except at low rain rate and Matrosov's estimator fails at low rain (for this reason they suggest a Z-R relation for low rain). The 4^{th} order polynomial method of $\log_{10}(R/N_w)$ vs. $\log_{10}(Z/N_w)$ has a very low average bias, which is expected because it was fitted to this data set (disdrometer). This also shows that the calibration and attenuation correction of radar measurements up to the disdrometer range was accurate enough. The N_w normalization method leads to a relatively reliable estimation of rainfall even at low rain with no need to use a data tuned Z-R relation.

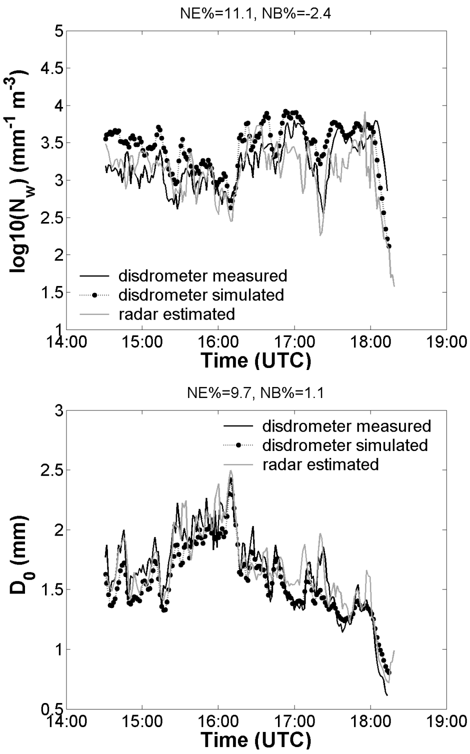

Fig. 5. As in Fig. 4 but for intercept parameter N_w and median volume diameter D_0 estimated from Eqs. (1) and (2).

Tables 1 and 2 show the normalized bias for various rain ranges in order to remove the bias effect of low mean value (most observed rainfall rates were moderate to low values) in error normalization and to show the variability of the error with rain intensity. In Table 1 the estimation of rain rates below 0.1 mm h^{-1}, which is not shown, is characterized by more than 50% overestimation with significantly lower bias for radar estimators with N_w normalization (the bias is near zero for the corresponding disdrometer estimators). This can be concluded from Fig. 6, too. Also, the statistics for rain rates higher than 40 m h^{-1} are not very reliable due to the limited number of observations at the disdrometer site in this rain range.

The behavior of each of the disdrometer estimators shows its theoretical capabilities, while the difference from the results of the corresponding radar estimator shows the applicability of the method to radar data. Possible effects of spatial variability of rain in the comparison of radar with in-situ measurements should appear as increased random error. According to the disdrometer estimates it can be concluded that the N_w normalization is in general beneficial. However, using the N_w estimated from polarimetric relations the nonlinear behavior of $\log_{10}(R/N_w)$ vs. $\log_{10}(Z_h/N_w)$ is modified and rainfall estimation using high order (4^{th}) polynomial may lead to reduced accuracy for moderate rain rates according to the results presented in Table 1. For the case of radar estimates the normalization method surprisingly gives even more significant improvement.

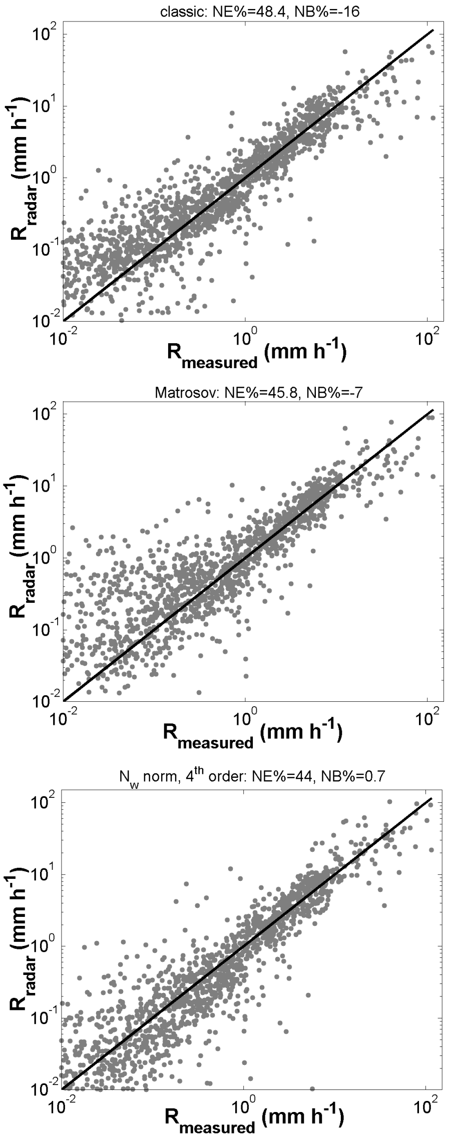

Fig. 6. As in Fig. 4 but scatter plots for all the rain events measured with the radar during the experimental period.

Table 1. Average normalized bias (%) of rainfall estimation by the disdrometer/radar (1-1.5 min time interval). Random error ranges from 30/70% at low rain rate to 20/30% at higher rain rate.

Rain (mm h^{-1})	0.1-1		1-10		10-40		40-120	
Classic	20	26	6	12	-17	-30	-24	-56
Matrosov	38	54	31	14	13	-13	8	-47
Park	-11	32	78	62	61	51	52	-2
N_w, Anagnostou	-12	-12	13	-5	10	-5	9	-34
N_w, 1st order	-5	-6	17	-2	11	-1	8	-31
N_w, 4th order	11	9	40	13	22	9	10	-30

Table 2. Average normalized bias (%) of 15 min accumulated rain estimation by disdrometer/radar. Random error ranges from 20/65% at low rain rate to 10/30% at higher rain rate.

Rain (mm)	0.01-0.1		0.1-1		1-10	
Classic	21	25	10	12	-8	-22
Matrosov	29	109	36	24	19	-15
Park	-35	33	69	94	66	38
N_w, Anagnostou	-25	-19	10	-1	9	-14
N_w, 1st order	-19	-11	15	5	10	-11
N_w, 4th order	-9	-2	39	24	19	-3

Accumulated rain estimates shown in Table 2 show less bias and random error as expected. However, more data points are needed for more reliable statistics.

5 Concluding remarks

It was verified that X-band radars can give accurate estimates of rain parameters despite considerable attenuation. N_W normalization improves at least the bias of the rainfall estimates. Variable coefficients in N_w based rainfall estimators did not give significant improvements probably due to errors in N_w estimation from polarimetric estimator. Finally, comparison of X-band rain estimates with disdrometer at longer distances (>30 km) should be carried out in order to verify the attenuation correction method at large distances.

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