Performance comparison of dual-polarization X-band path attenuation and rainfall microphysical estimates with measured disdrometer raindrop spectra

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Abstract

Recent research has demonstrated the value of polarimetric measurements for the correction of rain-path attenuation at X-band radar frequency and the estimation of rain parameters including drop-size distributions (DSD). The standard remotely-sensed precipitation products, from large operational S- or C-band network radars, have spatial resolutions that are often too coarse to reveal hydrological important spatial variability that compromise the prediction of floods. Dual-polarization X-band radar is a potential solution as a gap filling data source for such operational weather radar networks. The major issue in X-band rainfall estimation studies is the atmospheric attenuation effect. Measurements at X-band undergo severe co-polar ($A_H$) and differential ($A_{DP}$) attenuation that can cause significant reduction of the horizontal reflectivity ($Z_H$) and differential reflectivity ($Z_{DR}$) signal, which must be corrected because it introduces errors in the rainfall estimation. The fundamental aspect that brought X-band back to the interest of hydrometeorologists for rainfall estimation is that the horizontal versus vertical polarization differential phase shift $\Phi_{DP}$ measurement can be used for the effective estimation of specific copolar, $A_H$, and differential, $A_{DP}$, attenuation profiles. Attenuation corrected profiles are then used to derive the two parameters of the normalized gamma DSD model, that is, intercept ($N_W$) and mean drop diameter ($D_0$) while the third one (shape parameter $\mu$) is calculated using the constrained $\mu = D_0$ relation. This work will focus on the use of National Observatory of Athens’ (XPOL) X-band weather radar and 2D video-disdrometer (2DVD) observations, collected during the 2008-2009 in the urban area of Athens, Greece. The efforts are devoted to first (a) evaluate the performance of a newly devised attenuation correction scheme using coincident XPOL observations with measured spectra from a 2DVD, and then (b) compare a new optimized rainfall and drop-size distribution estimation algorithm with already published algorithms. These algorithms are evaluated and intercompared on the basis of in-situ disdrometer spectra observations.

1. Introduction

Flooding is still the most damaging of all natural disasters; one-third of the annual natural disasters and economic losses and more than half of all victims are flood related (Douben, 2006). In Europe, we count an average of 130 fatalities due to floods per year (Barredo, 2007); of these, 40% are due to flash floods. Flash floods are associated with heavy precipitation events induced often by rough orography as is the case for most of the storms in the Mediterranean coastal area or in the Alpine region in Europe. Most flash flood generating storms are associated with Mesoscale weather systems—that is, systems with horizontal scales of 10 to 1000 (km) (Borga et al., 2008). Therefore, advancing the quantitative precipitation estimation from remote sensing in mountainous regions is of great importance and practical use in improving the predictability of hydrological impacts such as flash floods and hydrogeological risks and facilitating efficient water management practices. Current operational rainfall monitoring systems based on national weather radar networks operating on the basis of long-range coverage do not provide sufficient measurements to support accurate estimations of precipitation.
variability in complex terrain. Studies have shown that precipitation estimation from conventional long-range weather radar observations is affected by significant systematic and random error associated with a host of sources ranging from the variability in the relationship for reflectivity to rainfall inversion to beam geometry and elevation issues including the rain-path attenuation of signal power, the vertical precipitation structure affecting higher elevation angles and longer ranges and the partial or total beam occlusion affecting lower elevation beams (e.g., Joss and Waldvogel 1990; Kitchen and Jackson 1993; Joss and Lee 1995).

In the past two decades studies have shown that polarization diversity in weather radar can improve the accuracy of rainfall estimation in different ways (Seliga and Bringi, 1976; Testud et al. 2000; Bringi and Chandrasekar, 2001; Bringi et al. 2004). Polarization diversity has a significant impact on attenuating frequency (X-band) radars advancing their potential for use in heavy precipitation estimation. Even though, the typical range of an X-band radar can be short (60-120 km) compared to the long-range operational weather radars (consisting primarily of S-band, e.g. WSR-88D network in US, and C-band radars, e.g., radar networks in Europe), these are low-power and cost effective systems that can be used to fill up critical gaps of the long-range national radar networks. Deployment of local X-band radars can be particularly important for monitoring small-scale basins in mountainous regions and urban areas that are prone to flash floods but are not adequately covered by existing long-range radar networks.

The primary disadvantage of X-band frequency is the enhanced rain-path attenuation in power related (Z_H and Z_DR) measurements as compared to the S-band (and to the moderate attenuation at C-band) frequency, including the potential for complete signal loss in cases of signal propagation through large paths (>10 km) of heavy rainfall (or mixed phase precipitation). Current research on X-band rainfall measurements shows that the fundamental issue of rain-path signal attenuation at X-band can be reliably resolved using the differential phase shift (Φ_DP) measurement (Anagnostou et al. 2004, 2006a, 2006b; Matrosov et al. 2005; Park et al., 2005). Furthermore due to the local deployment and the increased sensitivity of Φ_DP change to precipitation intensity (about three times that of S-band frequency), radar measurements at X-band may achieve higher resolution rain rate estimations than the lower frequency (C-band and S-band) operational radar systems, which is one of the critical issues for local flood applications.

However, there are several features of the X-band radar-rainfall measurement that need to be researched to understand the full potential of this radar frequency in flash flood applications. These include issues with respect to: (1) the effect of mixed phase precipitation along the radar ray on the accuracy of polarimetric based rain-path attenuation correction; (2) the consequential effect of attenuation correction uncertainty and Mie resonance effect on precipitation estimation in intense rain storms; and (3) the scale and range dependence of X-band rainfall estimation accuracy and the consequential impact on flood prediction accuracy in small scale basins.

2. Experimental area and data

To facilitate this study radar data collected with the National Observatory of Athens (NOA) dual-polarization X-band radar (hereafter named XPOL) and a 2D-video disdrometer (2DVD) deployed in a distance to each other of ~35 (km) for the period of 2008 to 2009, in the urban area of Athens, Greece. In Fig. 1 we show the location and measurement range of the XPOL radar and the in situ. The radar is positioned in the National Observatory of Athens Institute 500 (m) above the sea level, while the 2DVD deployed next to the cost on the roof of the Hellenic Center for Marine Research.

FIG. 1. Map of the experimental area showing the deployment site of the XPOL radar (NOA) and its coverage and the deployment site of the 2DVD (GV1)
The radar was operated remotely only when there was a forecast for rain event in the nearby area. The radar was operated first in a range height indicator (RHI) mode taking one measurement from over the GV1 and then in a planar position indicator (PPI) mode taking measurements in a 360-deg sector scan, at 0.5-deg and 1-deg elevation sweeps with its optimum highest range resolution (120 m) for the total range of 60 (km). Antenna rotation rate was 10 (° sec⁻¹) for PPI and 3 (° sec⁻¹) for RHI mode. The time period for a full volume scan was less than 3 minutes.

3. Path attenuation correction algorithm

The major issue in X-band rainfall estimation studies is the atmospheric attenuation effect. The major limitation is that measurements at X-band undergo severe co-polar (A_H) and differential (A_D) attenuation that can cause significant reduction of the horizontal reflectivity (Z_H) and differential reflectivity (Z_D) signal, which must be corrected because it introduces errors in the rainfall estimation.

The fundamental aspect that brought X-band back to the interest of hydrometeorologists for rainfall estimation is that the horizontal versus vertical polarization differential phase shift Φ_DP measurement can be used as a constraint parameter for the effective estimation of specific copolar, A_H, and differential, A_D, attenuation profiles (e.g., Testud et al. 2000; Matrosov et al. 2005; Anagnostou et al. 2006; Park et al. 2005). As shown by a recent elaborate study by Anagnostou et al. (2006), this aspect minimizes the uncertainty due to rain path attenuation at X-band due to the fact that Φ_DP is not affected by attenuation (provided that backscattering signals are above the minimum detectable level) and it is almost linearly related with the range integrated co-polar attenuation, expressed in dB. Once the A_H range profile is estimated by means of a rain path attenuation Φ_DP constrained technique, A_DP can then be retrieved directly from A_H given that A_H and A_DP are almost linearly related (i.e., A_H ~ A_DP).

We will explore a number of attenuation correction algorithms described in recent publications by Anagnostou et al. (2004, 2006a, 2006b, 2009), Matrosov et al. (2005) and Park et al. (2005). All these experimental studies have argued that Φ_DP can provide stable estimates of specific (A_H) and differential (A_D) parameters along a radar ray. Although these studies have commonly used Φ_DP as a constrain parameter for attenuation estimation they differ in terms of algorithmic structure. Matrosov et al. (2005) and Anagnostou et al. (2006a, 2006b) related the path-integrated A_H and A_D directly to Φ_DP using a linear model. The two methods differ in that Anagnostou et al. (2006a, 2006b) method assumed fixed values for the linear coefficients, while Matrosov et al. (2005) proposed an iterative solution where the coefficient values get updated iteratively on the basis of specific differential phase shift K_DP (the gradient of Φ_DP along range ray) and attenuation-corrected Z_H and Z_DR parameters. Park et al. (2005) on the other hand modified the self-consistent method of Bringi et al. (2001), originally developed for C-band frequency, to apply at X-band radar. The method assumes, similarly to the other methods, linear A_H - Φ_DP and A_D - A_H relationships and devises an optimization approach to determine coefficient values that maximize the consistency between estimated path-integrated attenuation and Φ_DP profiles.

The above two methods then will compared with a newly developed attenuation correction method (Kalogiros et al. 2010). Highly accurate (i.e., unbiased with about 15% standard error) relationships for A_H and A_D parameters with Z_H, Z_DR and K_DP for rain were estimated using T-matrix simulations at X-band for a wide range of parameters of droplet size distributions (assumed to be of normalized Gamma distribution type). A constrained shape parameter of droplet size distribution was assumed (Vivekanandan et al. 2004), which was verified by our extensive dataset derived from 2D video disdrometer observed spectra. These relationships are based on the theoretical limits for Rayleigh scattering (Bringi and Chandrasekar 2001) with the addition of droplet median volume dependence due to Mie scattering effects, which is approximated by rational polynomials as shown below:

\[ A_H = f(K_{DP}, Z_{DR}, D_Z) \]  \hfill (1)

\[ A_{DP} = f(K_{DP}, Z_{DR}, D_Z) \]  \hfill (2)

where the D_Z is the reflectivity-weighted mean droplet diameter (in the range of 0.5 to 7 mm):

\[ D_Z = f(D_{ZR}) \]  \hfill (3)

and the

\[ D_{ZR} = f(K_{DP}, Z_{DR}, Z_H) \]  \hfill (4)

is the Rayleigh like theoretical relationship for the estimation of D_Z. Z_H and Z_{DR} are given in mm³/m³ and linear units, respectively, K_{DP} is given in deg/km and A_H and A_{DP} units are dB/km. The complexity of the above relationships due to the rational polynomials is required in order to totally remove the bias which is varying with mean droplet diameter and is found in all previous relationships presented in the literature. Using D_Z instead of the median volume diameter (D_{m}) to describe the Mie effect error due to the physical variability of the shape parameter of droplet size distribution around the constrained value is significantly reduced.
The above relationships for attenuation coefficients are used in an iterative scheme in order to estimate the unknown cumulative path attenuation along each radar ray. The sensitivity of this attenuation correction method to absolute calibration errors is small and gives a random error in attenuation correction of about 15% when considering radar calibration errors of 1 dB for $Z_H$ and 0.2 dB for $Z_{DR}$. The method resembles the method of Gorgucci et al. (2006) in the sense that it estimates specific attenuation directly using all three polarimetric radar parameters and uses an iterative method along the radar ray to estimate the total path-integrated attenuation. However, in that case the corresponding relationships where retrieved from best fit (parameters tuning) of simulation results to a predefined power formulae instead of using the physical Rayleigh limits.

4.1 Performance evaluation of the “optimized” attenuation correction algorithm

With the addition of random noise on radar products and variable shape parameter $\mu$ of the DSD around its constrained value the bias error is almost zero, while the random error tends to 15% (relative standard error) at large $A_H$ values as shown in Fig.2. The relative error increases rapidly at low $A_H$, but the absolute error does not increase as it can be seen in the scatter plot. The error introduced by the variability of the drop size distribution (DSD) shape parameter $\mu$ is a random error of about 5% at large $A_H$. The variability of the DSD shape parameter was estimated from disdrometer data. However, at small values median volume diameter $D_0$ (i.e. low $A_H$) a significant part of this variability is not physical variability but it is due to measurement and statistical errors by the disdrometer. Thus, the actual $A_H$ error due to this factor should be smaller especially at low $A_H$ values. In addition, the axial ratio of rain droplets was assumed to vary randomly (with a standard deviation of 15%) around the equilibrium relationship. This introduced a small part of the random error (about 5% for large $A_H$) in the estimation of $A_H$, while error due to the radar products noise is the dominant error factor at about 13%.

Coïncident time series of radar observations over the 2DVD selected for the evaluation of the new developed “optimized” attenuation correction algorithm. This algorithm is compared with two well documented from the literature algorithms, the modified self-consistent algorithm of Park et al. 2005 (hereafter called Park) and the iterative approach of Matrosov et al. 2005 (hereafter called Matrosov). We select a number of ~4000 colocated in time (every three minutes) radar estimates and 2DVD spectra. Evaluation is performed based on visual and statistical comparison methods. Visual include frequency plots (Fig. 3) of the two algorithms from the literature (i.e., Park and Matrosov) compared to the new “optimized” algorithm in comparison to the corresponding $Z_H$ and $Z_{DR}$ from the validation site GV1. It is evident from the histograms of Fig. 3 that the corrected for attenuation $Z_H$ estimated from the new method is comparable to Park’s algorithm, where in turn both of them are similar to the 2DVD. On the other hand, the attenuation corrected $Z_{DR}$ estimated from Park’s algorithm is closer to the 2DVD measurements while the new method is overestimates values between 1 to 2.5 (dB). In both cases, Matrosov’s algorithm performs the worst.
Visual comparison also includes time series used to show the co-variation of the three techniques compared to the ground validation observations. Therefore, we select two characteristic rain events. The first one (28/03/2008) is a stratiform type with averaged 35-40 dBZ maximum reflectivities and total duration of the event of ~12 (hrs) and the second one (02/04/08) is a more convective type rain storm with averaged maximum reflectivities in the order of 50 (dBZ) and duration of 10 (hrs). The Fig. 4a and 4b are two panel figures, showing the time series from the (a) 28/03/08 and (b) 02/04/08 rain event comparisons of the three attenuation correction methods, the 2DVD measurements and the raw radar observations. On both plots, the upper panel is the $Z_H$ and the lower one is the $Z_{DR}$.

From the visual inspection of Fig. 4 we concluded that the new “optimized” method is comparable to the Park and the ground validation observations (2DVD) for both stratiform and convective type storms.

<table>
<thead>
<tr>
<th>$Z_H$/$Z_{DR}$</th>
<th>Correlation</th>
<th>Slope</th>
<th>$\text{rRMSE}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>“optimized”</td>
<td>0.892/0.644</td>
<td>1.011/1.104</td>
<td>0.156/0.683</td>
</tr>
<tr>
<td>Park</td>
<td>0.893/0.631</td>
<td>1.027/1.054</td>
<td>0.160/0.653</td>
</tr>
<tr>
<td>Matrosov</td>
<td>0.882/0.321</td>
<td>1.043/0.648</td>
<td>0.173/0.780</td>
</tr>
</tbody>
</table>
Table 1 summarizes the bulk error statistics (correlation, slope, and rRMSE) for all the collocated radar/2DVD observations. The statistics are computed for $Z_H$ greater than 10 dBZ and $Z_{DR}$ greater than 0 dB. A first observation from the bulk statistics confirm that the new “optimized” method is comparable to Park’s method and they show the best correlation (0.89) and lower bias (1.011 and 1.027, respectively) and relative error (0.156 and 0.160, respectively) for the $Z_H$. Similarly, for the $Z_{DR}$, they show comparable correlations (0.644 and 0.631, respectively) and similar errors and biases.

5. Rainfall microphysical algorithm

Rainfall varies both in space and time thus making its accurate estimation an extremely difficult task. Since radar does not measure rainfall directly but rather we relate the measured variable (e.g. radar reflectivity) with rainfall properties, accurate estimation of rainfall requires a model that would best describe the physical properties of rain formation. For decades rainfall estimates were derived from the single polarization radar measurement, i.e., the radar reflectivity factor ($Z$) (e.g., Atlas and Ulbrich, 1990; and Joss and Waldvogel, 1990). Dual-polarization offers more than one parameters ($Z_H, Z_{DR}, \Phi_{DP}$) that can facilitate the use of multi-parameter rainfall estimation algorithms. The relationships described in this section were derived from T-matrix scattering simulations (Ishimari 1991) based on a “normalized” Gamma distribution (Bringi and Chandrasekar, 2001) for the rainfall drop size distribution (DSD), a linear drop axis ratio model (Pruppacher and Bead, 1970; Matrosov et al. 2002) with a Gaussian distribution model with zero mean and 7.5-deg standard deviation for the droplets’ canting angle (Bringi et al. 2003) and a broad range of rainfall DSD parameters derived from high-resolution (1-min averages) spectral data. The dielectric constant of the water was evaluated for an average atmospheric temperature of 10 °C. Below we discuss the rainfall microphysical algorithm used in this study.

A new rainfall microphysics algorithm, developed from T-matrix simulations using the method described in section 4 (i.e. based on Rayleigh limit with the addition of a rational polynomial dependence on median volume diameter $D_0$ due to Mie scattering effects), will also be examined and compared to the existing dual-polarization techniques. The algorithm is given by the following relationships (Kalogiros et al. 2010). First the median volume diameter ($D_0$) is calculated using the following:

$$D_0 = f(D_z, Z_H, Z_{DR}, K_{DP})$$

(5)

then the intercept parameter $N_w$ is then calculated by the:

$$N_w = f(D_0, Z_H, Z_{DR})$$

(6)

while the shape parameter $\mu$ is constrained by the droplet size distribution (DSD). After we have estimate the parameters of the DSD we can in a more accurate way than the conventional ones to estimate rainfall with the following relation:

$$R = f(D_z, D_0, Z_H, Z_{DR})$$

(6)

where the median volume diameter $D_0$ (values in the range 0.5 to 3.5 mm), $Z_H$ and $Z_{DR}$ are given in mm$^6$/m$^3$ and linear units, respectively, and rainfall rate $R$ is given in mmh$^{-1}$.

6. Conclusion

In this study we investigate the performance of a newly developed attenuation correction and rainfall estimation algorithm. Initially, with the addition of random noise on the radar products and the variable shape parameter $\mu$ of the DSD around its constrained value the bias error is almost zero, while the random error tends to 15% (relative standard error). Then we used a large number of annual (2008-2009) X-band dual-polarization observations in the urban area of Athens, Greece. We compare the new “optimized” method with two documented from the literature algorithms and evaluated against ground validation observations taken from a 2D-video disdrometer. An overview of the bulk statistics and from the time series plots described in this study that for all the type of storms the attenuation correction estimated $Z_H$ and $Z_{DR}$ of the new “optimized” method are comparable to ground validation observations and to the Park method.

We develop a new rainfall microphysical algorithm from T-matrix simulations. The corrected for attenuation products estimated from the new “optimized” method will be used to estimate microphysical parameters and then in turn more accurate rainfall rate and accumulation estimates. This method will then evaluated and compared using the large number of annual coincident radar estimated products and spectra measurements taken from the 2D-video disdrometer. The new method will be compared to the rainfall microphysical algorithm discussed in section 5 and to different DSD algorithms taken from the literature.
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References


