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Experimental results on rainfall estimation in complex terrain with a mobile *X*-band polarimetric weather radar

Marios N. Anagnostou [a,*], John Kalogiros [b],
Emmanouil N. Anagnostou [a,c], Anastasios Papadopoulos [a]

[a] *Department of Inland Waters, Hellenic Center for Marine Research (HCMR), Greece*
[b] *Institute for Environmental Research and Sustainable Development, National Observatory of Athens, Greece*
[c] *Department of Civil and Environmental Engineering, University of Connecticut, Storrs, Connecticut, United States*

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ABSTRACT

In this work the capability of reliable rainfall measurements with small weather radars in complex terrain for flood forecasting purposes is examined. Rain measurements were carried out during winter–spring 2007 with a mobile X-band dual-polarization radar in the northwestern mountainous part of the island of Crete in Greece. In this area a 2D-video disdrometer and a network of raingauges was installed for radar calibration and evaluation of rainfall measurements, respectively. The complex terrain of the experimental site may significantly reduce the performance of rain measurements due to ground clutter and partial or total beam blockage. A beam blockage algorithm using high resolution terrain data was applied in order to find areas with significant terrain effects and estimate correction of the radar measurements. Rain attenuation correction was based on modern sophisticated algorithms using differential phase measurements. The accuracy of rainfall estimation from standard or polarimetric algorithms at plan position indicator (PPI) scans was examined for high-temporal resolution (1 min) rainfall rates and accumulated rainfall values for winter and spring time rain events. For high elevation measurements, which were required in order to avoid terrain effects in large areas of interest, a correction for the vertical-profile-of-reflectivity (VPR) was also applied to the radar data. An average VPR model used in the corresponding correction of reflectivity was constructed based on range–height indicator (RHI) scans. It was concluded that quantitative high resolution X-band radar observations of rainfall in complex terrain is possible after careful application of all the above processing steps.

1. Introduction

X-band (λ~3 cm) polarimetric weather radar systems provide a cost effective solution for high-resolution precipitation observations due to their small size and low demand in transmitter power. The introduction of polarimetric approaches in *X*-band systems can now account for the attenuation and differential attenuation effects (Testud et al., 2000; Matrosov et al., 2002, 2005; Anagnostou et al., 2006a,b, 2007) which used to be a significant drawback for the use of *X*-band frequencies in quantitative precipitation estimation (QPE). Such estimates from *X*-band dual polarization radar systems can be used to fill in spatial coverage gaps of the large low-frequency (*C*-/*S*-band) operational weather radars and to provide high-resolution rainfall observation over small scale mountainous basins and urban areas. Measurements provided by dual-polarization observations in addition to the horizontal polarization reflectivity (Z_H) provided by standard single polarization systems are the differential reflectivity, (Z_{DR}), i.e. the ratio of horizontal to vertical polarization reflectivity, the differential propagation phase shift (Φ_{DP}) and copolar correlation coefficient (ρ_{hv}).

In addition, *X*-band weather radars are more suitable for small range flood studies in complex terrain. However, the

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[*] Corresponding author. Hellenic Centre for Marine Research—Institute of Inland Waters, 46.7 km Athens-Sounion Ave., P.O. BOX 712, GR-19013, Anavissos Attikis, Greece.
E-mail address: managnostou@ath.hcmr.gr (M.N. Anagnostou).

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deployment of operational weather radars in mountainous terrain introduces issues as a result of the partial or complete beam blockage of the ray due to the ground clutter at low radar scan elevations. For QPE in complex terrain, radar rain measurements are taken at higher elevation scans, which are related to rapid increase of radar beam height with distance, in order to avoid either ground clutter or blockage from the terrain. This observational geometry in combination with low height of the freezing level causes significant errors in rainfall estimation because the radar resolution volumes are probably located in the melting layer or snow regions (Kitchen and Jackson, 1993) even if it rains on the ground. The beam interception through precipitation melting regions is often associated with an enhancement of the reflectivity. The primary cause of this reflectivity enhancement (bright band, BB) is the rapid increase in the dielectric constant of hydrometeors at the top of the melting layer followed by an increase of the fall velocities of melting snowflakes toward the end of the melting process (Fabry and Zawadzki, 1995).

In this paper, we present an evaluation of available processing methods for *X*-band polarimetric radar over complex terrain. The difference from previous studies is that we evaluate the combination of all the processing steps (beam blockage, rain attenuation, rainfall algorithm, vertical profile of reflectivity-VPR) for an *X*-band weather radar in an integrated fashion for a difficult case due to terrain limitations. In Section 2 we discuss a standard and two advanced *X*-band polarimetric algorithms for rainfall estimation, while in Section 3 we discuss the study area and data acquired with the *X*-band mobile radar (XPOL) of the National Observatory of Athens during two major rain events, a stratiform event during winter (04/01/2007) and a more convective event during spring time (22/03/2007). In Section 4 we qualitatively compare the rainfall algorithms for the lowest elevated gauges, close to the coast. In Section 5 we identify the problem of estimating rain in high elevation, we introduce the already available VPR correction algorithm and we show the results for the highland gauges. Finally, Section 6 contains the conclusions of this work.

2. The XPOL algorithm

2.1. Polarimetric radar variables

As stated in the introduction the polarimetric radar parameters used in quantitative rain estimation are the horizontal polarization reflectivity, Z_H (mm^{6}m^{-3}), vertical polarization reflectivity (Z_V, mm^{6}m^{-3}) and differential reflectivity, Z_{DR} (dB) and the specific differential propagation phase shift, K_{DP} (° km^{-1}). These variables depend on the raindrop size distribution, DSD, and the drop scattering amplitudes as follows (Brandes et al., 2004):

$$Z_{H,V} = \frac{4\lambda^4}{\pi^4|K_w|^2}\int_{D_{min}}^{D_{max}} |f_{HH,VV}(D)|^2 N(D)dD \tag{1}$$

$$Z_{DR} = 10log\left(\frac{Z_H}{Z_V}\right) \tag{2}$$

$$K_{DP} = \frac{180\lambda}{\pi}\int_{D_{min}}^{D_{max}} \mathrm{Re}[f_{HH}(0,D) - f_{VV}(0,D)]N(D)dD \tag{3}$$

where D (mm) is the raindrop sphere equivalent volume diameter and $D_{\min}$ and $D_{\max}$ are the diameters of smallest and largest drops in the distribution. The $f_{HH,VV}(D)$ and $f_{HH,VV}(0,D)$ are the backscattering and the forward scattering amplitudes of a drop at horizontal and vertical polarization, respectively, K_w is the dielectric factor of water, λ (cm) is the radar wavelength, and $N(D)$ (mm^{-1}m^{-3}) is the count of raindrop of size D per unit volume. The $f_{HH,VV}(D)$ and $f_{HH,VV}(0,D)$ parameters depend on the assumed raindrop shape-size relationship as discussed in subsequent section. The horizontal polarization reflectivity, Z_{mH} (mm^{6}m^{-3}), and differential reflectivity, Z_{mDR} (dB), measured by the radar at range gate "r", are related to the corresponding intrinsic (non-attenuated) radar parameters (Z_H and Z_{DR}) as follows:

$$Z_{mH}(r) = Z_H(r) \times 10^{-0.2\int_0^r A_H(s)ds} \tag{4}$$

$$Z_{mDR}(r) = Z_{DR}(r) \times 10^{-0.2\int_0^r A_{DP}(s)ds}. \tag{5}$$

A_H and A_{DP} (dB km^{-1}) are the co-polar specific and differential rain-path attenuation, respectively. Quantitative use of *X*-band radar data in estimation of precipitation parameters (rainfall rates, water content, raindrop size distribution) requires knowledge of the non-attenuated radar parameters (i.e., Z_H and Z_{DR}), which is a subject discussed next.

2.2. Rain attenuation correction

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 constraining parameter for the effective estimation of specific copolar, A_H, and differential, A_{DP}, attenuation profiles (e.g., Testud et al., 2000; Vulpiani et al., 2005; Matrosov et al., 2002; Anagnostou et al., 2006a,b; Park et al., 2005a). As shown by Anagnostou et al., (2006a,b), this aspect minimizes the uncertainty due to rain path attenuation at *X*-band due to the fact that Φ_{DP} is not a power related parameter (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., $A_H \propto A_{DP}$).

The attenuation correction method used in this study 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 each ray in separate rain cells defined by correlation between polarization channels higher than 0.8. In addition, each rain cell along a radar ray was further checked for *sub-cells* in order to avoid the wrong detection of possibly merged neighboring cells using only the ρ_{HV} correlation limit. This would affect the attenuation correction method because rain cells may have different rain microphysical parameters and, thus, different parameters of signal attenuation. The *sub-cells* were detected from significant peaks of K_{DP}, which were identified as a factor of 2 change of K_{DP} between a local maximum (peak) and adjacent minima. Neighboring *sub-cells* with too short (3 km length limit) or too