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Performance evaluation of high-resolution rainfall estimation by X-band dual-polarization radar for flash flood applications in mountainous basins

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SUMMARY

Different relations between surface rainfall rate, R, and high-resolution polarimetric X-band radar observations were evaluated using a dense network of rain gauge measurements over complex terrain in Central Italian Alps. The specific differential phase shift, K_{DP}, rainfall algorithm (R_{KDP}) although associated with low systematic error it exhibits low sensitivity to the spatial variability of rainfall as compared to the standard algorithm (R_{STD}) that is based on the reflectivity-to-rainfall (Z–R) relationship. On the other hand, the dependence of the reflectivity measurement on the absolute radar calibration and the rain-path radar signal attenuation introduces significant systematic error on the R_{STD} rainfall estimates. The study shows that adjusting the Z–R relationship for mean-field bias determined using the R_{KDP} estimates as reference is the best technique for acquiring unbiased radar-rainfall estimates at fine space–time scales. Overall, the bias of the R_{KDP}-adjusted Z–R estimator is shown to be lower than 10% for both storm cases, while the relative root-mean-square error is shown to range from 0.6 (convective storm) to 0.9 (stratiform storm). A vertical rainfall profile correction (VPR) technique is tested in this study for the stratiform storm case. The method is based on a newly developed VPR algorithm that uses the X-band polarimetric information to identify the properties of the melting layer and devices a precipitation profile that varies for each radar volume scan to correct the radar-rainfall estimates. Overall, when accounting for the VPR effect there is up to 70% reduction in the systematic error of the 3° elevation estimates, while the reduction in terms of relative root-mean-square error is limited to within 10%.

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 (Gaume et al., 2009). Most flash flood generating storms are associated with Mesoscale weather systems—that is, systems with horizontal scales of 10–1000 km (Borga et al., 2008). Generally, complex topography can exaggerate the spatial variability of rainfall, since synoptically forced flows toward and over a topographic barrier may interact with and enhance storm dynamics (Smith, 1979). This may lead to slow-moving or quasi-stationary storms that due to local terrain-morphology can produce heavy rainfall associated with both increased rain durations and intensities over small areas (Rotunno and Ferretti, 2001; Medina and Houze, 2003). Oftentimes, storms developing in mountainous regions are affected by a boundary layer jet (influenced by a stalled frontal boundary) that feeds near-saturated air, thereby creating well-organized formations of precipitation through warm rain processes at relatively low levels in the storm (Petersen et al., 1999; Smith et al., 2000; Kelsch, 2001). This low level enhancement effect of rainfall intensity creates a real challenge for remote sensing (both ground radar and satellites) detection. For ground radars in particular monitoring long ranges, issues with partial beam blockage of the lower beam elevations or with the overshooting of low-level convection signatures by the upper elevation beams may lead to significant range dependent errors in precipitation estimation (White et al., 2003; Smith et al., 2005). In addition, melting snow in widespread storm systems resulting in intense and persistent surface rainfall may substantially increase the threat of flooding in complex

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terrain basins (Barros and Kuligowski, 1998; Smith et al., 2005). 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., Zawadzki, 1984; Austin, 1987; 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, 1978; Testud et al., 2000; Bringi and Chandrasekar, 2001; Bringi et al., 2002, 2004). Polarimetric information introduces along with the horizontal polarization (Z_H in dBZ) reflectivity measurement additional parameters such as the differential reflectivity (Z_{DR} in dB—the ratio of the horizontal to vertical polarization reflectivity) and the differential propagation phase shift (Φ_{DP} in °). The Φ_{DP} is a powerful radar parameter for use in quantitative precipitation estimation (QPE) because it is immune to signal power issues, i.e., the attenuation from rainfall or other atmospheric sources and the absolute radar calibration (Ryzhkov and Zrnic, 1996; Testud et al., 2000; Gorgucci et al., 2001, 2002; Bringi and Chandrasekar, 2001; Bringi et al., 2002; Brandes et al., 2003; Anagnostou et al., 2006a,b; Matrosov et al., 2002, 2005). Furthermore, the availability of multiple partially-independent parameters available for any single radar sampling volume can now facilitate precipitation classification and rainfall drop size distribution estimation, which in turn can further improve the rainfall estimation accuracy (Gorgucci et al., 2000, 2001; Brandes et al., 2004; Bringi et al., 2002, 2004; Matrosov et al., 2005).

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,b; 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.

In this work we devise an experimental study to evaluate the use of locally-deployed X-band dual-polarization radar for estimation of rainfall at high spatial and temporal scale over complex terrain. We present a comprehensive error analysis evaluating different rainfall algorithms and the use of a vertical rainfall profile correction technique in high-resolution quantitative precipitation estimation. The study is based on two precipitation systems representing different rainfall intensities as well as spatial and vertical structures. The novelty of this work is the use of a dense mountainous network of rain gauges providing "ground truth" rainfall observation at different ranges from an X-band dual-polarization radar (from 5 up to 60 km). In the following section we present the study area and experimental data, while in Section 3 we present the rainfall algorithms and the vertical profile of rainfall structure correction technique investigated in this study. In Sections 4 and 5 we present the evaluation results and discuss our conclusions and recommendations for future research in Section 6.

2. Experimental area and data

The study is based on radar data collected with the National Observatory of Athens (NOA) dual-polarization X-band radar (hereafter named XPOL) deployed in an experimental area of the Northeast Italian Alps over a period of three months (August–October, 2007). The area is part of a Hydro-meteorological Observatory (HO) that provides data on flash floods for a project named HYDRATE (Hydro-meteorological data resources and technologies for effective flash flood forecasting) funded by the European Commission. In Fig. 1 we show the location and measurement range of the XPOL radar and the *in situ* rain gauge network (50 tipping bucket gauges) providing half hourly rainfall measurements within the XPOL radar range. As shown in the figure, the XPOL observations cover an experimental basin of 1200 km^2 (named Bacchiglione) and its sub-basin Posina (125 km^2). The altitude range of the experimental area is from 100 to 2500 m above sea level (a.s.l). The area frequently receives very intensive rainstorms, resulting in severe erosion and flash floods (particularly in the Posina basin). This steep environmental gradient from North to South is associated with climatic differences (Dinku et al., 2002), e.g., annual precipitation ranges from 2000 to 1000 mm per year and mean annual temperatures from 5 to 14 °C. Below we provide description of the XPOL and rain gauge data.

The XPOL radar was placed 4 km south of the city of Folgaria, in the Italian Alps (see Fig. 1) at 1650 m a.s.l. 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 two RHI measurements from 0° to 45° elevations and then in a planar position indicator (PPI) mode taking measurements in a 360° sector scan, at 2° and 3° elevation sweeps with its optimum highest range resolution (120 m) for the total range of 50 km. Antenna rotation rate was $10^\circ\ s^{-1}$ for PPI and