Investigation of dual polarization techniques for operational rainfall estimation in complex orography

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1. Introduction

Rain rate fields represent a valuable information not only for hydro-geological applications, but also for microwave communication planning and for assimilation purposes within numerical weather forecast models (e.g., Rinehart and Garvey 1978; Lee et al. 1995; Germann and Joss 2002). In presence of a complex orography, characterized by hilly and mountainous scenarios, rain rate estimation is fairly involved especially if needed at a ground resolution less than few kilometers (Marzano et al. 2004). Rain gauge networks denote many limitations related to their sparse and spot-like data distribution. Nevertheless, they represent indispensable means for remote-sensor adjustment (often referred as calibration) and validation (Gourley et al. 2006; Vulpiani et al. 2009).

Microwave weather radars are considered a fairly established technique to retrieve rain rate fields on large areas from measured reflectivity volumes. After decades of scientific research following the first pioneering paper, weather radar polarimetry is increasing in popularity within operational meteorological services (Bringi and Chandrasekar 2001). Several recent studies and field campaigns have demonstrated the advantages of an operational radar upgrade to polarimetric capabilities. Benefits of weather radar polarimetry at C-band include improved data quality and hydrological product accuracy, self-consistency techniques for assessment of system miscalibration and automatic echo classification for weather and forecasting applications (Gorgucci et al. 1999; Straka et al 2000; Marzano et al. 2008). Polarimetric methods to correct for the effects of attenuation in rain through the use of differential phase measurements have also renewed the interest for quantitative precipitation estimation at C- and X-band frequencies (e.g., Testud et al 2000; Vulpiani et al. 2005; Marzano et al. 2007; Vulpiani et al. 2008a).

Radar observations are affected by several impairments which should be carefully evaluated, especially in a complex orographic environment (Marzano et al 2004; Gourley et al. 2006). Together with the enhancement of ground-clutter effects, the major limitation is represented by partial or total beam blocking caused by natural obstructions which very often impose scanning elevations higher than 1.5°. These range-related limitations tend to reduce the potential role of operational weather radars in monitoring precipitation amount at ground within mountainous areas since, if the nature or intensity of rainfall varies with height (e.g., melting effects during stratiform rain), radar returns at higher altitudes may be not representative of surface rain rate (Vulpiani et al. 2009).

Some of these effects have been investigated, and possibly mitigated, by using data acquired by the C-band dual-polarized radar located at Mt. Il Monte near Tufillo (Chieti, central Italy) and a network of about 50 raingauges within the radar nominal coverage of 175 km. In particular, the work is finalized to: i) clutter removal through the synergy of empirical clutter map and polarimetric texture analysis; ii) correction of two-way path attenuation; iii) reconstruction of vertical profile of reflectivity; iv) polarimetric estimate of near-surface rainfall. Several techniques, approaching the previous problems, are inter-compared and evaluated.

2. Radar polarimetric C-band system

The “Il Monte” radar belongs to the Italian network which provides a coverage of most of Italian territory with update every 15 min and ground spatial resolution lower than 1 km. The primary justification for a weather radar network in Italy is the detection and warning of severe weather and related hydro-geological risks. The hydrological risk is further enhanced by the orography, which is in Italy characterized by small catchments along most coastlines.
and by the Alpine and Apennine chains. Due to the incomplete national coverage, the Department of Civil Protection (DPC) has been appointed to be responsible for complementing and integrating the existing systems, made of ten C-band installations belonging to Regional Authorities, five of which polarimetric and one transportable X-band polarimetric radar, two systems owned by the Italian company for air navigation services (ENAV) and three managed by the Meteorological Department of the Italian Air Force (AMI).

The Polarimetric Doppler Radar System (PDRS), located at Mt. Il Monte, is one of the new six installations directly managed by DPC. The Il Monte radar is located near the border between the Molise and Abruzzo region, as shown in Fig. 1. It operates at 5.6 GHz and is connected by satellite links to the two National Radar Primary Centers (NRPC), one located in Roma (managed by DPC) and one in Savona (managed by CIMA Research Foundation), in order to mainly ensure the remote control (through the Radar Remote Control (RRC) server) and products generation. The RPC located in Savona works as “backup centre” in order to continuously ensure the system functioning. The subsystem RAC (Radar Archive Centre) is devoted to archive and manage radar data and products by means of a relational database. The generated products are then disseminated to all institutions composing the national network (Vulpiani et al. 2008b).

FIG. 1. Digital Elevation Map centered on the Il Monte-radar (indicated by a red cross) coverage (Abruzzo, Italy).

Data processing includes artifacts suppression, path-attenuation correction, hydrometeor classification, vertical profile of reflectivity correction and rainfall estimation. Continuous improving of such processing and products has been dealing with the cooperation of several Italian centers competent on radar meteorology. The operational processing chain is implemented within the system DATAMET® (software system for radar remote control, product generation, visualization, maintenance, and data archive) developed by Elsag-DATAMAT SpA. The DATAMET is an IDL®-language-based open and fully-customizable system which offers the opportunity to develop, improve and implement new algorithms.

3. Ground rain depth retrieval methodology

PDRS are capable to measure the dual-polarization response due to precipitating particles. A normalized Gamma particle size distribution (PSD) is usually introduced in literature to account for most of the variability occurring in the naturally observed raindrop, and more in general, hydrometeor dimensional spectra (Straka et al., 2000; Marzano et al., 2007). The number N(D) of particles per unit volume per unit size can be analytically written assuming an equivalent spheroidal shape. The copolar radar reflectivity factors $Z_{hh}$ and $Z_{vv}$ at horizontal (H) and vertical (V) polarization state, the cross-polar reflectivity factor $Z_{hv}$, the differential reflectivity $Z_{dr}$ and the linear depolarization ratio $L_{vh}$ can be expressed as follows (Bringi and Chandrasekar, 2001):

$$Z_{hh}, Z_{vv}, Z_{hv}, Z_{dr}, L_{vh}$$
\[ Z_{hh,vv,lv} = \frac{\lambda^4}{\pi^2} \left| K \right|^2 < 4\pi |S_{hh,vv,lv}^b(D)|^2 >, \quad Z_{dv} = \frac{Z_{hh}}{Z_{vv}}, \quad L_{hh} = \frac{Z_{vh}}{Z_{hh}} \]  

(1)

where \( S_{hh,lv} \) and \( S_{lv} \) are the backscattering co-polar and cross-polar components of the complex scattering matrix \( S \) of a raindrop, and the angular brackets represent the ensemble average over the PSD. The parameter \( K \) depends on the complex dielectric constant of water estimated as a function of wavelength \( \lambda \) and temperature \( T \).

For a polarimetric radar, the specific differential phase shift \( K_{dp} \), due to the forward propagation phase difference between H and V polarization and co-polar correlation coefficients \( \rho_{hv} \) can be obtained in terms of the scattering matrix \( S \) as:

\[ K_{dp} = \lambda \cdot \text{Re}[<F_{hh}(D) - F_{vv}(D)>], \quad \rho_{hv} = \frac{\langle S_{vv}^* S_{hh} \rangle}{\sqrt{\langle |S_{hh}|^2 \rangle \langle |S_{vv}|^2 \rangle}} = |\rho_{hv}| e^{j\delta_{hv}} \]  

(2)

where \( F_{hh,lv} \) are the forward-scattering co-polar components of \( S \) and \( \delta_{hv} \) is the volumetric backscattering differential phase.

The specific attenuation \( A_{hh} \) at H polarization and the differential attenuation \( A_{dp} \) are finally defined as:

\[ A_{hh} = 2\lambda \text{Im}[<F_{hh}(D)>]; \quad A_{dp} = A_{hh} - A_{vv} \]  

(3)

where specific attenuations are intended to be one-way. A correct microphysical and dielectric modeling of hydrometeors is essential to obtain meaningful simulations of polarimetric radar measurements. Detailed information about polarimetric radar signatures of several hydrometeor types can be found in Straka et al. (2000) and Marzano et al. (2007).

FIG. 2. Effective Visibility Map (EVM) for the elevations 0.8 deg (Fig. 2 a) and 3.0 deg (Fig. 2 b), respectively. The 20-dBZ occurrences are color coded.

3.1 Polarimetric clutter removal

As a recent component of the Italian radar network, the radar Il Monte location (700 m asl) resulted from the compromise between the radar network fulfilling needs and logistics and environmental requirements. The radar location is surrounded in north-western side by the highest peak (the Gran Sasso mountain is about 3000 m high) of the Appenine mountain range (see Fig. 1); furthermore, the Maiella mountain (the highest peak is of about 2800 m) at distance of about 35 km causes the main beam blocking toward the inland country. In such circumstances the major error sources in radar rainfall estimation are obviously related to ground clutter contamination, partial and/or total beam shielding and vertical variability of reflectivity.
In order to properly take into account the effects induced by the complex orography surrounding the radar site, an Effective Visibility Map (EVM) has been directly retrieved from the radar observations instead of using an electromagnetic propagation model to identify the obstructed radial directions (see Fig. 2). EVM is computed from the normalized Volume of Occurrences (VO) of reflectivity echoes greater than 20-dBZ (named VO20). Considering a sufficiently large dataset (composed by rainfall and clear air observations), the normalized VO20 as a function of \((r,\theta,\phi)\) can be interpreted as the probability to find a radar echo greater or equal to 20 dBZ at a given spatial point \((r,\theta,\phi)\). The shielded sectors are identified as those characterized by EVM\(<\text{Threshold1}\); the fixed echoes (ground clutter) are identified by the condition EVM>\text{Threshold2}.

It is worth mentioning that both thresholds depend on the data set characteristics (precipitation pattern, intensity, etc.); however, \text{Threshold1} is typically lower than 1% while, for a sufficiently large data set, an upper threshold of 50 % was found suitable for identifying the fixed echoes. As it can be seen by Fig. 2 a), showing the EVM at 0.8 degrees of antenna elevation, the free azimuthal sector is less than 200-degrees wide. According to the retrieved EVM, the minimum unshielded antenna elevation is of about 3 degree. Consequently, the effective maximum radar coverage is reduced to about 50 km (as illustrated in Figure 2 b).

The EVM enables either the evaluation of the shielded azimuthal sector or the identification of the fixed echoes (static clutter map), the latter having the higher occurrences (see for example the red dots in figure 2a). Echoes generated by non-meteorological targets (i.e., ground-clutter, biological targets, RLAN interferences) are identified and cancelled out by resorting to a Fuzzy Logic scheme considering the following input crispy variables: static ground clutter reflectivity map, radial velocity \(v\), correlation coefficient \(\rho_{hv}\), texture of \(Z_{dr}\) and \(\Phi_{dp}\). The EVM is then applied to identify and skip shielded echoes.

**FIG. 3.** Hourly Cumulated Rainfall (HCR [mm]) as estimated by the considered algorithms with respect to gauge observations in the visible sector within 100 km of range distance. The rainfall algorithms are applied to LBM.
3.2 Near-surface rain-rate estimation

The complete processing chain can be summarized in the following few steps:

i. Clutter identification and cancellation;
ii. Differential phase filtering and $K_d$ retrieval. A moving-window linear fitting is applied jointly with a preliminary median filtering.
iii. Attenuation and differential attenuation compensation by applying the Adaptive PhiDP (APDP) procedure (Vulpiani et al., 2008a).
iv. Spatial-mean vertical profile of reflectivity either at horizontal or vertical polarization is computed for each volume scan in order to retrieve the near surface field of $Z_h$ and $Z_v$ and, consequently, of $Z_{hv}$.
v. Rainfall estimation.

Single and multi-parametric rainfall estimation algorithms are applied with different processing-chain complexity in order to separately evaluate each error source:

1. $R(Z_b)$, where $Z_b$ is only corrected for non-meteorological targets;
2. $R_{APDP}(Z_b)$, where $Z_b$ is corrected for non-meteorological targets and rain path attenuation applying the APDP procedure;
3. $R_{APDP,VPR}(Z_b)$, where $Z_b$ is corrected for non-meteorological targets, rain path attenuation and VPR;
4. $R(Z_b, Z_h)$, where $Z_b$ and $Z_h$ are only corrected for non-meteorological targets;
5. $R_{APDP}(Z_b, Z_h)$, where $Z_b$ and $Z_h$ is corrected for non-meteorological targets and rain path attenuation applying the APDP procedure;
6. $R_{APDP, VPR}(Z_b, Z_h)$, where $Z_b$ is corrected for non-meteorological targets, rain path attenuation and VPR.

The mono-parametric rainfall algorithm is the well-known Marshall and Palmer (1948): $Z_v=200 R^{1.6}$; the polarimetric procedure is based on the use of reflectivity and differential reflectivity (Bringi and Chandrasekar, 2001): $R=aZ_b/Z_{hv}$ ($a=5.8 \times 10^{-3}$, $b=0.91, c=-2.09$). Once the instantaneous rain rate $R$ is estimated, the comparison with gauge stations has been performed on Hourly Cumulated Rainfall (HCR) basis.

4. Case study and results

The selected case study and the results, obtained by applying the previously illustrated radar retrieval methodology in complex orography, are presented in the following sub-sections.

4.1 Gauge-radar intercomparison

In the present work the stratiform event observed on Nov. 28, 2008 in central Italy has been considered as a case study. Once defined the error as the difference between the radar estimate and rain-gauge observation of $HRC: \varepsilon = HCR_R - HCR_G$, the relative performance of the considered rainfall algorithms is evaluated in terms of mean error ($Bias$), error standard deviation ($STD$) and Root Mean Square Error ($RMSE$), separately for the visible and shielded sectors.

Fig. 3 shows the Hourly Cumulated Rainfall as obtained by applying the considered algorithms to the reflectivity (and differential reflectivity) Lowest Beam Map (LBM) in the visible sector within 100 km of range distance. Similarly, Fig. 4 shows the results obtained by applying the considered rainfall algorithms to the VMI maps in the shielded sector within 50 km of range distance. The comparison between radar estimates and gauge observations has outlined the following main considerations:

- within the visible sector (figure 3) the ground projection from the VPR correction does not improve the rainfall retrieval. Indeed the use of the LBM seems to guaranty a good representativeness of surface rainfall;
- within the shielded sector the use of the VMI maps enable to reduce the effects of partial beam blockage even though the probability to intercept the bright band is higher. Indeed, the overestimation effect (e.g., figure 4 panel a and b) by the radar, when the shielded sectors are considered, seems to confirm the bright band contamination;
- except for a few local areas in the shielded sector, characterized by moderate precipitation rates, the effects of rain path attenuation compensation are negligible mainly due to the stratiform nature of the considered event;
- within the shielded sector, some minor effects are found by also applying the VPR correction. Indeed, we have found $RMSE=1.63$ (with $Bias=-0.49$ and $STD=1.45$) for $R_{APDP, VPR}(Z_b)$ and $RMSE=1.7$ (with $Bias=-0.24$ and $STD=1.49$) for $R(Z_b)$.
due to the weak intensity of the considered event, no relevant benefit has been obtained by applying the polarimetric rainfall algorithms.

FIG. 4. Hourly Cumulated Rainfall (HCR [mm]) as estimated by the considered algorithms with respect to gauge observations in the shielded sector within 50 km of range distance. The rainfall algorithms are applied to VMI.

4. Conclusions

A preliminary study for evaluating the potential benefit of dual polarization rainfall algorithms in complex orography is accomplished. At the moment the study has only outlined that in such environmental conditions dual-polarized radar systems guaranty a general data quality improvement by enabling the use of more efficient artifacts suppression techniques.

Future works will be devoted to deeply analyze several convective rainfall events in order to assess the impact of attenuation correction and multi-parametric rainfall algorithms on quantitative precipitation estimate.

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References


