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Reconstruction of reflectivity vertical profiles and data quality control for C-band radar rainfall estimation

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Abstract. Microwave Doppler radars are considered a fairly established technique to retrieve rain rate fields from measured reflectivity volumes. However, in a complex orographic environment radar observations are affected by several impairments which should be carefully evaluated. 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 to scan at high-elevation angles. 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 either 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. Therefore, before to use the radar data, it is necessary to reduce, as much as possible, this evaluation errors and to estimate the reliability of the processed data. Near to the quality control, are needed quality indexes, taking into account each correction and elaboration step, that could be useful to retrieve a final quality value. In this work, we analyse the main factors that could be affect the efficiency of a reconstruction methodology of near-surface reflectivity fields from high-elevation reflectivity bins, in presence of complex orography. A climatologic schema is applied to infer near-surface reflectivity at a given range interval. The technique is developed in polar coordinates partially taking into account the antenna beam width degradation at longer ranges and overall computational efficiency for operational purposes. Thereafter, it is applied on a rainfall event observed by a C-band Doppler radar operating in S. Pietro Capofiume (Bologna, Italy) and the relation between the reconstruction error and possible quality indicators is analysed and discussed.

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1 Introduction

Rain rate fields represent a useful information not only for hydro-geological applications, but also for microwave communication planning and for assimilation purposes within numerical weather forecast models (as pointed out, among others, by Borga et al., 2000; Bauer et al., 2002; Marzano et al., 2004a). In presence of a complex orography, characterized by hilly and mountainous scenarios, this task is fairly involved especially if needed at a ground resolution less than few kilometers square. Rain gauge networks denote many limitations related to their sparse and spot-like data distribution (Ciach and Krajewski, 1999; Fornasiero et al., 2004). Nevertheless, they represent "standard" means for remote-sensor calibration and validation.

Radar observations are affected by several physical effects which should be carefully evaluated, especially in a complex orographic environment (Kitchen and Blackhall, 1992; Joss and Lee, 1995; Andrieu and Creutin, 1995; Marzano et al., 2004b; Fornasiero et al., 2004). Together with the enhancement of ground-clutter effects, the major limitation is represented by partial or total beam blocking caused by natural obstacles which very often impose scanning higher elevation angles larger 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 either the nature or intensity of rainfall varies with height (e.g., melting effects during stratiform rain), radar returns at higher altitudes may be not directly representative of surface rain rate (Germann and Joss, 2002; Marzano et al., 2004).

A conventional approach to the reconstruction of surface rain rate fields is to estimate the vertical profile of reflectivity factor (VPR) by using proper spatial and time averages of radar volume data (Koistinen, 1991). This approach, which might be classified as "static", is strongly affected by the variability of rain at medium and small scales. Various regimes can be present over large areas, mainly stratiform, convective and orographically enhanced. Stratiform rain is recognizable by a decreasing reflectivity profile and by the presence of a bright band, just below the freezing level and with a thickness dependent on the thermal lapse rate and fall velocity. On the contrary, convective rain is featured by a VPR mainly constant with altitude due to the mixing of ice and water hydrometeors sustained by strong updrafts and downdrafts. Finally, orographic rain may present largely variable reflectivity at low levels due to windflow over mountain slopes. As opposed to a "static" approach to rain field reconstruction, a "dynamic" (or adaptive) technique should be able to exploit "real-time" or "quasi real-time" measured reflectivity data available at unobstructed heights to estimate the unknown radar reflectivities at lower levels, including that near the surface.

This ability to retrieve VPR at small scales can be addressed by resorting to either a classification or to an estimation method. In the first case, the main goal is to identify a typical VPR given an upper-level set of reflectivity data (Gray et al., 2002; Koistinen and Pohjola, 2002; Franco et al., 2002). The considered VPR classes can be simply stratiform and convective or, using a more sophisticated approach, can be categorized according to the fine variability of the reflectivity measurements. On the other hand, in order not to be limited by the definition of a "typical" profile, the training data set, possibly classified, can be used to set up inversion algorithms able to use, in a statistical way, the information of measured reflectivity every scan (Marzano et al., 2002). A major limitation of both the approaches is related to the choice and statistically significance of the training data set. A real-time operational aim may strongly orient the decision on the solution strategy for VPR reconstruction. All processing steps must employ computing resources for a time much less than that taken for a complete radar volume scan. This means that the processing of the volumetric data must be fast enough and avoid any large data backlog.

In order to accomplish this task, two ways may be envisaged. The first approach, here referred to as "on line", is to estimate a space-time average VPR from near-real time volume data within fairly limited areas and amount of time (e.g., from 5 up 140 km and from 15 min to few hours) (Germann and Joss, 2002). The simplicity of the "on-line" VPR reconstruction would ensure a high-speed profile correction procedure. The second approach, referred to as "off-line", is to resort to a training of the VPR retrieval algorithm by using historical radar volume data sets, possibly classified in time and space (Franco et al., 2002; Marzano et al., 2004). After the training step is accomplished by using inversion techniques, the application of the VPR "off-line" reconstruction algorithm would become straightforward and fast. Both approaches have strengths and drawbacks: i) the "on-line" approach does not involve any historical data set even though a data pre-analysis should be necessary, but it has basically to resort to the use of simple estimation techniques; ii) the "off-line" approach can deal with more accurate inversion methods, but requires a training period of activity. The choice between the two strongly depends on the goals. To a certain extent, a synergistic approach might be the optimal solution.

As, previousy pointed out by Kitchen and Jackson (1993) and Kitchen (1997), the accuracy of reconstructing a near-surface rain field is intrinsically connected to its range dependence. If we consider, for example, an antenna beamwidth of 1°, the transverse dimension of the resolution volume ranges from 0.3 km at 20 km to 2 km at 120 km. It is obvious that non-uniform beam filling and smoothing effects can become significant as more as far from the radar site. A way to reduce this intrinsic limit is to perform an "identification" of VPR, i.e. deconvolve the radar observation by knowing the radar antenna pattern in order to retrieve the non-smoothed VPR (Andrieu and Creutin, 1995). It is worth mentioning that the identification of VPR is a different procedure from the reconstruction of VPR since in the latter case, after performing or not a VPR identification (possibly accomplishing it beyond a range of 60 km).

The overall objective of our efforts is to propose a combined processing technique to check for anomalous propagation and beam blockage coupled with a reconstruction methodology of near-surface reflectivity fields from high-elevation reflectivity bins in presence of complex orography. In particular in this work we focus our attention to identify the factors that condition the quality of the VPR. Climatological and adaptive schemes are applied to infer near-surface reflectivity at a given range interval. The techniques are developed in polar coordinates taking into account the antenna broadening at longer ranges and the overall computational efficiency for operational purposes. A case study, related to rainfall events observed by a C-band Doppler radar, is illustrated and preliminary results discussed.

2 Radar data and case study

Data were provided by C-band operational Doppler of S. Pietro Capofiume (Bologna, Italy), placed along the Reno river valley in northern Italy. This dual-polarization radar is placed on a tower with a Cassegrain parabolic antenna (without radome cover), providing a half-power beam-width of 0.9° and a directivity of about 45-dB. The klystron peak-power is 250 kW at 5.6 GHz with an alternating horizontal-vertical polarization transmission and dual pulse repetition frequency (PRF) system for unfolding capability. Pulse widths of 0.5 μs (i.e., short pulse with a resampled bin resolution of 250 m) and 1.5 μs (i.e., long pulse with a resampled bin resolution of 1000 m). The receiver sensitivity is equal to -113 dBm. The typically used maximum range is 250 km (with long pulse) and 125 km (with short pulse) for the intensity and velocity mode, respectively. A self-contained software is used to remotely operate and archive radar data.

Radar data are acquired with a prescribed scanning strategy during operational activity, consisting of 15 elevations with an angular spacing of 1°. Procedures to correct for gas absorption and to remove ground-clutter echoes using a Doppler filter are routinely applied. Side-lobe effects at very short ranges (less than 20 km) for low elevations are avoided by choosing higher elevations not affected by this effect.

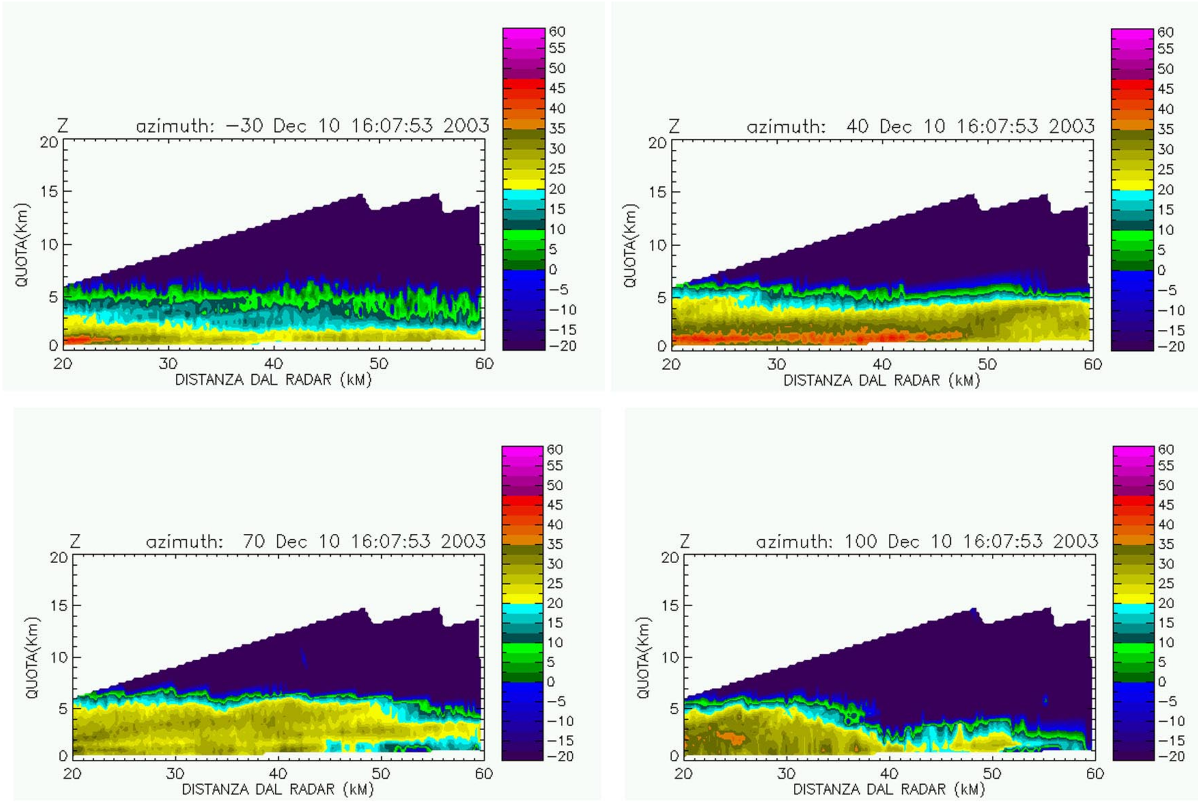

Fig. 1. 10/12/2003, 16:07 UTC. RHI (Range Height Indicator) of Reflectivity factor (dBZ) at different azimuths.

The case study is related to an event, occurred from 10 December 2003 to 11 December 2003 in the North of Italy. In the time range between 3 p.m. of 10th and 4 a.m. of 11th it has been collected 51 polar volumes, every 15 min and using the 15-elevations scan strategy ranging from 0.5° to 15°.

The case analysed was mainly characterised by a stratiform structure as shown (Fig. 1) in the vertical cut of the reflectivity factor (hereinafter refer as reflectivity Z), nevertheless some "mixed" areas not clearly classifiable are present in the event considered. Indeed while at −30° and 40° azimuth degrees the cloud structure highlight a stratiform behaviour, where it is quite evident the presence of a strong bright band echo at 40°, at 70° and 100° the pattern is quite different and the VPR shape is not totally conserved (the bright band is not so evident).

This can introduce a worsening in the quality of the mean VPR reconstruction, in particular in absence of a preliminary pixel to pixel rain classification.

3 Retrieval of the vertical profile of reflectivity

As already mentioned, the easiest way to reconstruct the VPR is to calculate its mean shape and, assuming it to be uniform in the whole radar domain, to retrieve the reflectivity at the desired level by the simple adding of a constant quantity (in dBZ units), as is further discussed in the following.

The assumption of a uniform-shape of VPR can be made more strength if we distinguish the different types of precipitation and retrieve distinct VPRs for each type. In this work the uniformity hypothesis has been restricted, in range, at rings of 5 km width, initially, and thereafter of 1 km of width, but without classification of the pattern type. As stated before, the main goal of the study is, in fact, to identify the factors that condition the quality of the VPR, even if the tested method is not yet the optimum. The choice to retrieve an average VPR for each constant-width ring also reflect the effect of the radar beam broadening that implies an increase of the radar cells volume with the distance. To calculate the VPR, it has been chosen the 3-D azimuth sector, relatively free of obstacles and covering the Po valley, between −90° and 135° and into the distance range [20, 60] km from the radar. Inside each circular sector, as define above, the individual points for each considered elevations is given by $\Delta R/dR$, where ΔR is the sector width and dR the minimum resolution (i.e. 250 m for the considered case). The total number of points of each "mean" profile is equal to $n*15$ where 15 are the elevations in the operational mode.

We have observed that, in spite of the averaging in time (over the whole event) and azimuth direction done, a certain amount of range variability is still present. In Fig. 2 it is represented the "time-azimuth averaged" profile at 25 km distance obtained using the 5-km rings and the 1-km rings and assuming for Z a minimum threshold of 0 dBZ. It is well

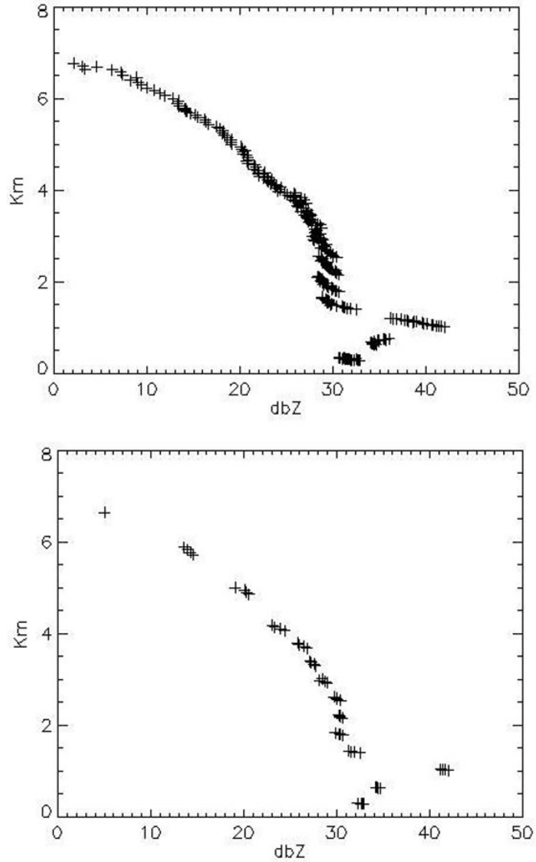

Fig. 2. Spatial-Time mean VPR at 25 km distance from radar, obtained using rings width of 5 km (above) and of 1 km (below). The VPR is calculating using the whole dataset event, composed of 51 polar volumes.

evident, in this figure, which up to 3 km above the ground a quite high variability is present within each elevation. Causes for this are probably due to the portion of the radar beam, outside the 3 dB width, that intercepts the bright band and to the inhomogeneous beam filling. Of course this problem is much more evident in the profile at the 5-km horizontal resolution that at 1-km. In order to overcome this problem a vertical interpolation at 0.2 km steps has been carried out (see Fig. 3). Observing the reconstructed VPR, in order to reduce the oscillations still visible above the bright band, the best choice appears to be the use of the 1 km width for the rings.

4 VPR correction and quality control issues

Once the mean shape of the VPR in each circular sector has been identified the reflectivity value at the desired height can be obtained by adding a constant to the data at lowest available elevation. As uniform mean shape, we intend that the value of Z at each height h, normalized with respect to the value at a generic height h_{ref}, is constant. This assumption can be done for each pair of heights. Thus, if we know the mean VPR and we aim to retrieve the Z value at the height

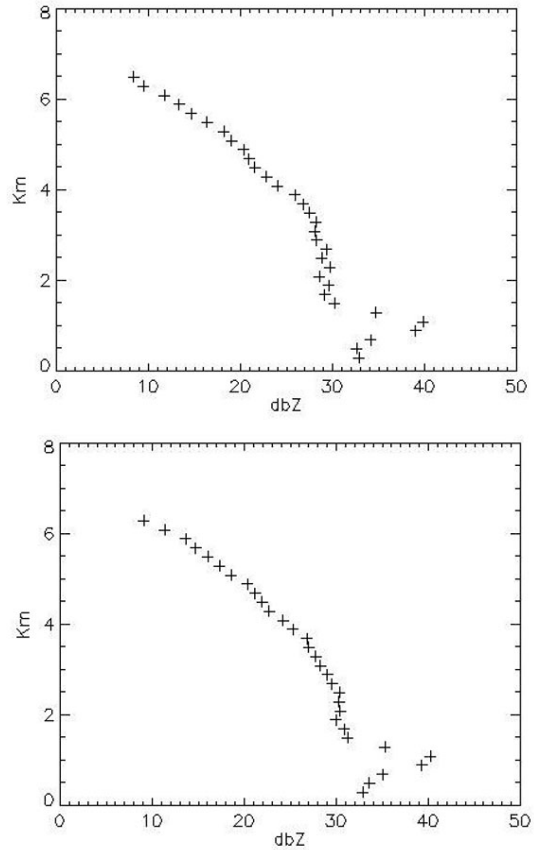

Fig. 3. As Fig. 2, but after a vertical interpolation every 0.2 km.

h_1 from the value at height h_2, we have (following, among others, Koistinen, 1991; and Koistinen and Pohjola, 2002):

$$c_{i,1,2} = \frac{\breve{Z}_i(h_1)}{\breve{Z}_i(h_2)} \quad (1)$$

where $\check{Z}$ is the mean value of Z available from the VPR and $c_{i,1,2}$ is the related constant, note that the "i" index refers to the i-th circular sector. The previous equation expressed in dBZ unit (i.e. in logarithmic scale) is used for estimate the unknown value of the reflectivity factor; it becomes:

$$\hat{Z}_{i\mathrm{dBZ}}(h_1) = c_{i,1,2\mathrm{dB}} + Z_{i\mathrm{dbZ}}(h_2) \quad (2)$$

where $Z_{i\mathrm{dBZ}}$ is the observed value at the lower and $\hat{Z}_{i\mathrm{dBZ}}$ is the estimated one.

As an example of the correction the reflectivity maps in a single instant, with and without VPR correction, are shown in Fig. 4. The main problem seems to be the extension of the VPR outside the selected bounds. In particular, near the radar and outside the selected sector data are partially affected by the bright band, this leads to an underestimation of the absolute correction in this area that is visible on the right panel. The position of the freezing level respect to the selected area, and its variability into the map, could be considered as another index of the VPR correction quality.

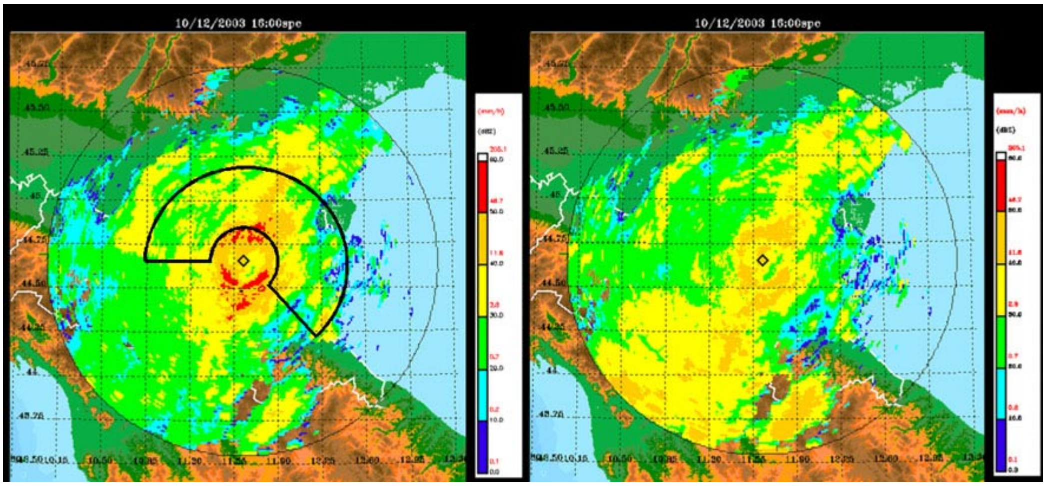

Fig. 4. 10/12/2003, 16:00 UTC. Reflectivity map without (on the left) and with VPR reconstruction (on the right). The boundary of the selected area used to retrieve the mean VPR is indicated in black on the left panel.

The rain type variability, the antenna pattern, the inhomogeneous beam filling, among others factors, can compromise the uniform shape assumption, so that a quality control of the VPR reconstruction and of its representativeness is necessary. Indeed, if we compare the mean VPRs at different distances from radar and a single time instantaneous VPRs (see Fig. 5), we can appreciate the VPR variability in range and time due not only to geometric reasons (i.e. the beam broadening), but also to meteorological causes. It is quite evident for example that at 3 km height the "mean" VPRs are within, roughly, 5 dBZ interval while the instantaneous one are within 15–20 dBZ interval. The reader should note that this is a key factor in the evaluation of the representativity of Z reconstruction.

In order to assess the quality of the estimated data, we have calculated, for each range bins in the whole free sector where the mean VPRs are estimated, the Z values at the lower elevation (Z_0), supposed that they are missing due to possible obstacles. Thus the error between the retrieved values and the "true" observed values of Z_0 has been computed, accordingly to the definition as follows:

$$\varepsilon_i = \hat{Z}_{i,\mathrm{dBZ}}(h_1) - Z_{i,\mathrm{dbZ}}(h_1) = \hat{Z}_{i,0} - Z_{i,0} \qquad (3)$$

Again, as a representative example, the azimuthal-average value of the error ε_i has been calculated vs. distance, for a single instant and displayed in Fig. 6. These errors are compared with the mean errors obtained used, as proxy for the value Z_0, the second elevation data as an estimate, as could be usually done in an operational context. In this figure it is shown how the 1-km rings width permits to reduce the bias, within a [−2, 2] dB interval, with respect to the 5-km width choice. Notice that the error due to VPR correction is considerably lower than that one obtained by the use of the "supposed first" available elevation, a [−4, 5] dB interval.

In the same way, it has been evaluated the instantaneous root mean square error (rmse) versus distance (see Fig. 7),

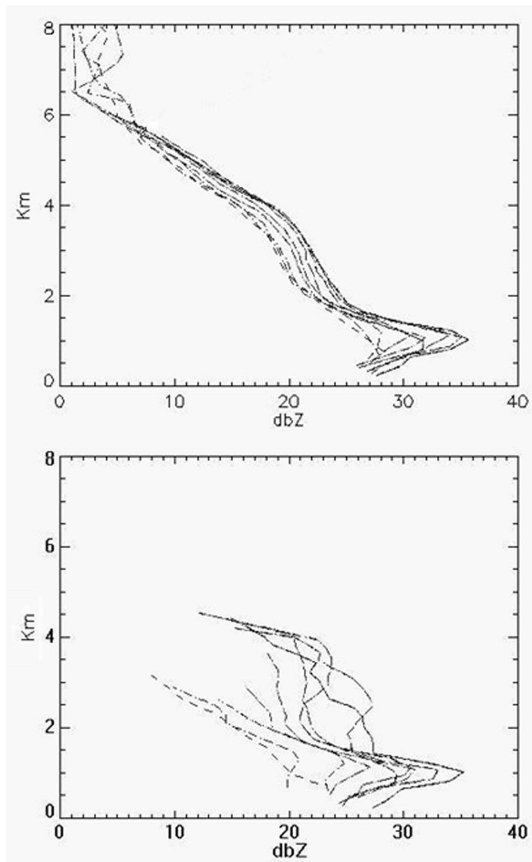

Fig. 5. VPR estimated at 1 km annular rings ranging from 20 to 60 km from the radar every 5 km steps. Upper panel: Mean VPRs over the whole event. Lower panel: Instantaneous VPRs at 10/12/2004, 15:00 UTC.

compared with the standard deviation the "$Z_1 - Z_0$" quantity. The reason is that this quantity could be estimated in real-time to give a quality indicator on the VPR reconstruction.

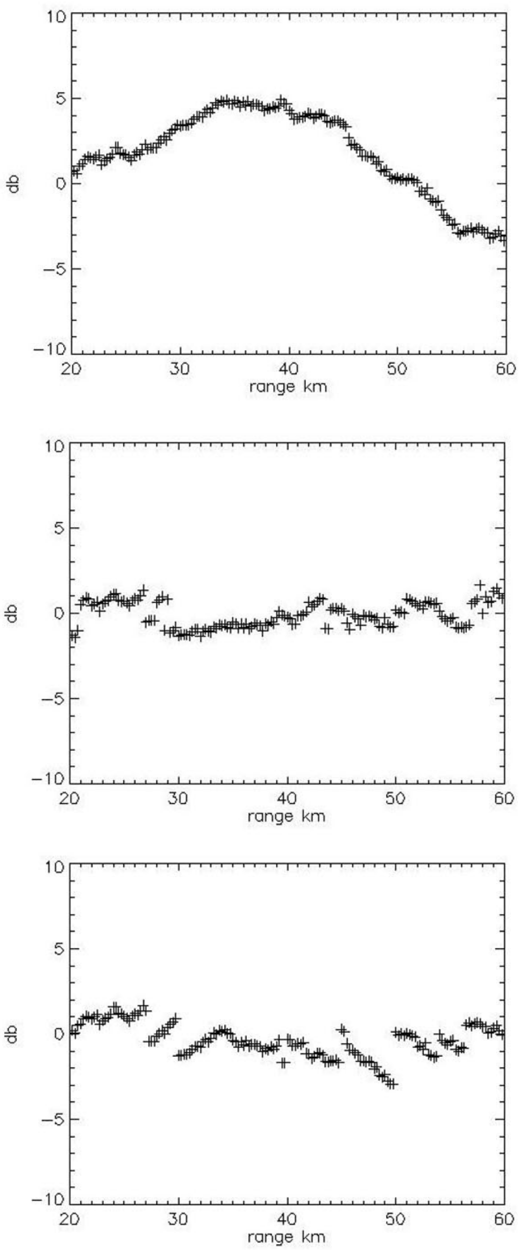

Fig. 6. Azimuthal mean differences (dB) between estimated Z and observed one using different methodologies for the 10/12/2003, 16:00 UTC data. Upper panel: $Z_1 - Z_0$. Middle panel: $\hat{Z}_{i,0} - Z_{i,0}$ using 1 km rings width. Lower panel: $\hat{Z}_{i,0} - Z_{i,0}$ using 5 km rings width.

The trend of these plots is quite similar, so we are confident that the standard deviation of $(Z_1 - Z_0)$ is a possible indicator of the quality of the VPR correction.

5 Conclusions

A preliminary work on the analysis of VPR reconstruction has been carried out. When this, as well as other correction techniques, is applied to the volumetric radar data in order to

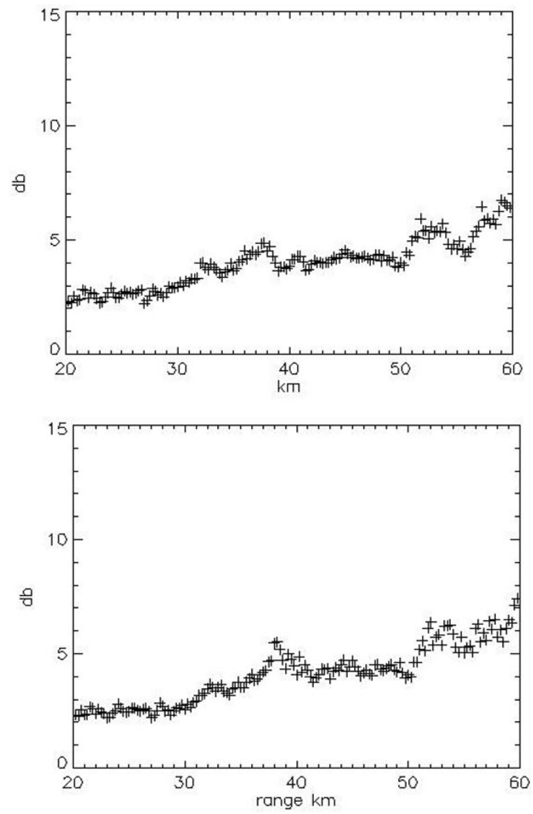

Fig. 7. 10/12/2003, 16:00 UTC. Upper panel: root mean square error of the reconstructed data at Z_0 using 1 km ring width. Lower panel: standard deviation of the $Z_1 - Z_0$ quantity, vs. distance from radar.

estimate the surface rainfall amount, it is important to give also, if it is possible, an estimate, disregarding that could be a very rough one, of the uncertainty, or if you want of the quality, of the products. Within in this context, the present work, aims to address the down to ground extrapolation.

In this regards the results show the following:

– A very import variability, both spatial and temporal, is present in the instantaneous VPR;

– A careful choice as to be taken in the definition of range resolution for the definition of "mean" VPR;

– The VPR technique is able to reconstruct data with an mean error slightly higher than the nominal 1 dBZ error present in the original data;

– The real-time standard deviation, which could be estimated from the lowest elevations, is a promising quantity to assess the quality of the reconstruction technique.

A more deep analysis, over a number of different meteorological situations, will be carried out in future. Following the results obtained, with this preliminary work, we are confident that a quality index, based on range resolution and estimated vertical variation, could be established for the VPR methodology and used in a more broad environment.

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References

Andrieu, H. and Creutin, J. D.: Identification of vertical profiles of radar reflectivity for hydrological applications using an inverse method, Part I: Formulation, J. Appl. Meteor., 34, 225–239, 1995.

Bauer, P., Mahfouf, J. F., Olson, W. S., Marzano, F. S., Di Michele, S., Tassa, A., and Mugnai, A.: Error analysis of TMI rainfall estimates over ocean for variational data assimilation, Quart. J. Roy. Meteor., 128, 2129–2144, 2002.

Borga, M., Anagnostou, E. N., and Frank, E.: On the use of real-time radar rainfall estimates for flood prediction in mountainous basins, J. Geophys. Res., 105, D2, 2269–2280, 2000.

Ciach, G. J. and Krajewski, W. F.: Radar-rain gauge comparisons under observational uncertainties, J. Appl. Meteor., 38, 1519–1525, 1999.

Fornasiero, A., Amorati, R., Alberoni, P. P., Ferraris, L., and Taramasso, A. C.: Impact of combined beam blocking and anomalous propagation correction algorithms on radar data quality, 3rd European Radar Conference, Visby, pp. 216–222, 2004.

Franco, M., Sempere-Torres, D., Sanchez-Diezma, R., and Andrieu, H.: A methodology to identify the vertical profile of reflectivity from radar scans and to estimate the rain rate at ground at different distances, 2nd European Radar Conference, Delft, pp. 299–304, 2002.

German, U. and Joss, J.: Mesobeta profiles to extrapolate radar precipitation measurements above the Alps to ground level, J. Appl. Meteor., 41, 542–557, 2002.

Gray, W. R., Uddstrom, M. J., and Larsen, H. R.: Radar surface rainfall estimates using a typical shape function approach to correct for the variations in the vertical profile of reflectivity, Int. J. Rem. Sens., 23, 2489–2504, 2002.

Joss, J. and Lee, R.: The application of radar-gauge comparisons to operational precipitation profile corrections, J. Appl. Meteor., 34, 2612–2630, 1995.

Kitchen, M.: Towards improved radar estimates of surface precipitation rate at long range, Quart. J. Roy. Meteor. Soc., 123, 145–163, 1997.

Kitchen, M. and Blackhall, R. M.: Orographic rainfall over low hills and associated corrections to radar measurements, J. Hydrology, 139, 115–139, 1992.

Kitchen, M. and Jackson, P. M.: Weather radar performance at long range – Simulated and observed, J. Appl. Meteor., 32, 975–985, 1993.

Koistinen, J.: Operational correction of radar rainfall errors due to the vertical reflectivity profile, Proc. 25th Radar Meteorology Conf., Paris (F), pp. 91–94, 1991.

Koistinen, J. and Pohjola, H.: Operational vertical reflectivity profile correction in radar network composites in Finland, Second European Radar Conference, Delft (NL), 18–23 Nov., 2002 (abstract).

Marzano, F. S., Vulpiani, G., and Picciotti, E.: Reconstruction of rain rate fields in complex orography from C-band radar volume data, 2nd European Radar Conference, Delft (NL), 18–23 Nov. 2002, pp. 227–232, 2002.

Marzano, F. S., Picciotti, E., and Vulpiani, G.: Rain field and reflectivity vertical profile reconstruction from C-band radar volumetric data, IEEE Trans. Geosci. Rem. Sens., 42, 4, 1033–1046, 2004a.

Marzano, F. S., Palmacci, M., Giuliani, G., Cimini, D., and Turk, J.: Multivariate Statistical Integration of Satellite Infrared and Microwave Radiometric Measurements for Rainfall Retrieval at the Geostationary Scale, IEEE Trans. Geosci. Rem. Sens., 42, 4, 1018–1032, 2004b.