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A methodology to identify the vertical profile of reflectivy from radar scans and to estimate the rainrate at ground at different distances

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Abstract. A methodology to identify the Vertical Profile of Reflectivity (VPR) from volume radar scans at different distances from the radar is presented. The identification is done averaging the apparent vertical profiles observed near the radar. Then, the estimated Mean Apparent Vertical Profile of Reflectivity (MAVPR) is used to obtain the rain-rate at ground at further distances from the radar. This is done fitting the shape of the MAVPR on the observed apparent values of reflectivity at these distances. A simulated case study is analysed in order to evaluate the performance of the proposed methodology.

1 Introduction

One of the main errors affecting weather radar estimates of the rainfall field at ground is produced by the vertical variation of the reflectivity. Near the radar the measures recorded in the firsts PPI's do not stand excessively above the ground and they are able to provide reasonable estimates of the rain-rates. However at further distances from the radar, due to the earth curvature and to the elevation angle of the beam, the heights of the observations increase considerably, and no negligible errors related to the vertical profile of reflectivity become severe. A critical situation happens in stratiform rain when the first elevation intercepts the bright band (enhancement of the reflectivity around the 0° C isotherm), producing a significant overestimation of the rain-rate. An additional source of error is given by the combination of this vertical variation of the reflectivity with the increasing beam width with distance. The conjunction of both factors leads to an important smoothing effect over the reflectivities observed by the radar (from now on, the apparent reflectivities), which are in fact averaged reflectivities by the beam pattern. So, beyond of a certain distance out of the radar, the measures are not able to reproduce correctly the vertical structure of the reflectivity field. Especially if a strong vertical gradient is present (i.e., in presence of bright band).

The correction of these errors due to the vertical variation of the reflectivity is usually done identifying the vertical profiles of reflectivity (VPR). Once it has been identified, it can be used to obtain the values of the rain intensity at ground from the measures of reflectivity available at a certain height above. However, to identify the shape of the vertical profile from the radar data is a kind of inverse problem because the radar measures are degraded (convolved by the beam pattern) and different vertical profiles could originate the same radar apparent measures.

Several Methods following different strategies have been developed to identify the vertical profile of reflectivity from radar data. A first group are the methods which propose to estimate an average profile from the radar data recorded in the proximity of the radar, and afterwards apply it to the entire radar domain. Koistinen (1991) averaged the radar data inside a range of 45 km from the radar and registered in a time interval of 24 h. Joss and Lee (1995) estimate an average VPR inside a range of 70 km during an interval of 5 min. Finally Germann and Joss (2002) proposed a methodology, which they called the Mesobeta Profile, consisting on an averaging scale of 70 km in range and few hours in time. They do it in order to find the scale that better solves the spatial and time variability of the real vertical profiles.

The second group of methods follow the outline started by Kitchen and Brown (1994) for a stratiform precipitation case. They suppose that the profile in each 7 km $\times$ km pixel agrees with a previously defined shape depending on several parameters defining the bright band characteristics and the variation of the reflectivity out of the bright band. Some of this parameters are fixed, other would be obtained using meteorological surface observations and IR satellite data, and the rest, depending on the reflectivity below the bright band, would be determined from the radar data measured in the pixel. Smtyth and Illingworth (1998) generalized Kitchen's Methodology separating between stratiform and convective precipitation using the Linear Depolarization Ratio. They identify the profile in the stratiform areas as Kitchen did it

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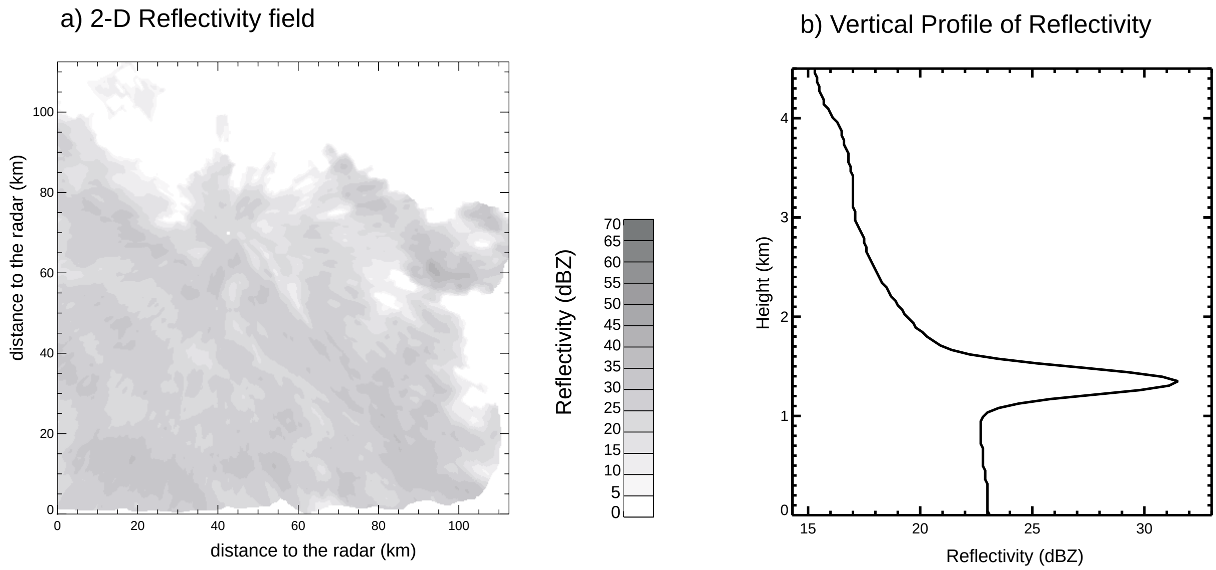

Fig. 1. (a) Image of the 2-D reflectivity field at ground obtained from the lowest horizontal plane of a Cartesian volume of reflectivity (250x250x250 m resolution). It has been generated densifying a real volume scan (see, Sánchez-Diezma, 2001; Sánchez-Diezma et al., 2001a; Sánchez-Diezma et al., 2001b). **(b)** Vertical Profile of Reflectivity recorded by a UHF high resolution profiler (data provided by the Marshall- Palmer observatory at McGill University, Canada; see Bellon et al., 1997). Both, the high density 2-D reflectivity field and the VPR registered by the UHF profiler are used to generate the 3-D reference rain fall field.

and they use a climatological profile in the convective ones.

Finally the philosophy of the methods proposed by Andrieu et al. (1995) and Vignal et al. (1999) is to recover the most probable VPR compatible with the radar measures using a statistical inverse method. This methodology is also able to identify local profiles but is very sensitive to the election of the *a priori* VPR shape selected for the initialisation of the inverse method.

The objective of this paper is to propose and evaluate a methodology, in the line of the previously developed by Joss and Lee (1995), which would allow us to identify the shape of the vertical profile of reflectivity from the observed volume scans in the nearest area to the radar, and then apply it to the furthest one. From an operational point of view the interest of this method lies in its simplicity, and additionally in the possibility of estimating the profile shape just from observed radar data instead of introducing an imposed a shape.

In the next sections a methodology to identify the VPR shape near the radar and to use it at further distances is proposed. A simulated case study to analyse its suitability for VPR's affected by the bright band is also showed. The simulation process consists on (i) building a 3-D rainfall field which will be taken as the reference rainfall field, and (ii) simulating the volume scans observed by a radar located at different distances from the rainfall. So, this procedure allows us to obtain a polar volume scan of apparent reflectivity values to apply our methodology and also it provides the original rainfall field which will be used as a reference to evaluate the performances of the model.

Table 1. Properties of the C-band radar of the Spanish Institute of Meteorology (INM) located near Barcelona

Frequency	5600–5650 MHz
PRF	250 Hz
Pulse length	2 μs
Beam width	0.9°
6-dB Receptor band width	1 MHz
Number of azimuths	420/rotation
Elevation angles	20
Distance between ranges	2 km
Maximum range	240 km

2 Data generation

A dense 3-D rainfall field (250 × 250 × 45 m resolution) has been generated using a two dimensional field of reflectivity, which introduces the horizontal variability, plus a common vertical profile of reflectivity everywhere (the same in the whole field). The two dimensional field (see Fig. 1a), representative of the rain at ground comes from the lowest horizontal plane of a Cartesian volume of reflectivity (250 × 250 × 250 m resolution), generated densifying a real volume scan (see Sánchez-Diezma, 2001; Sánchez-Diezma et al., 2001a; Sánchez-Diezma et al., 2001b). The vertical profile has been obtained from data recorded by a UHF high resolution vertical profiler (data provided by the Marshall-Palmer observatory at McGill University, Canada; see Bellon et al., 1997, and Fig. 1b).

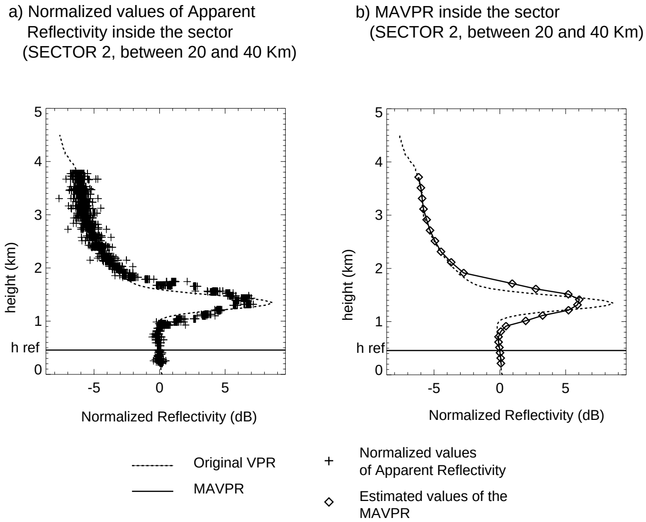

Fig. 2. Application of the proposed methodology to estimate the Mean Apparent Vertical Profile of Reflectivity (MAVPR) in a sector. In **(a)** the values of the normalized reflectivity associated to each observed value are showed. The height href is the reference level chosen for the normalization. In **(b)** the points of the MAVPR obtained applying a moving average process are showed.

To simulate the radar measures of apparent reflectivity the radar beam pattern has been convolved with the reference rainfall field according to the radar equation. The simulated scanning strategy and radar characteristics reproduce those of the C-band radar of the Spanish Meteorological Office (INM) located at Barcelona (see radar characteristics at Table 1).

The stratiform profiles as the one used here, shows a peak of reflectivity associated to the melting snow layer below the 0° C isotherm. Above the so called bright band, the reflectivity values decrease with height and below it the reflectivity remains practically constant until the ground (see Fabry and Zawadzki, 1995 for more information). So, because of their bright band, the stratiform profiles present the strongest vertical gradients of reflectivity and the most important VPR errors are related to them. In case that only the bright band is scanned it may be produced an overestimation of the rain intensity at ground in a factor of 5. If the first elevation angle overshoot the bright band an underestimation is produced. The chosen study case is one representative of stratiform rain, showing a clear bright band profile and able to cause the most important errors related to the VPR.

Because of the spatial homogeneity of the VPR used on the generated field, our study will be focused on the evaluation of how the methodology is influenced by the horizontal variability of the rainfall field, by the degradation of the radar measures with the distance and by the scanning strategy of the radar. The possibility of changing the vertical profile shape has not been taken into account, up to now, and lies out of the scope of this work.

3 Estimation of a MAVPR in a sector

The algorithm of estimation of the Mean Apparent Vertical Profile of Reflectivity (MAVPR) has been designed to calculate it on annular sectors placed at a certain distance from the radar, and it uses polar data. The first step to obtain the mean profile shape from all the apparent profiles inside the sector is to normalize these profiles respect the reflectivity at a common reference height level. This step should be done in order to make comparable the information of each profile of apparent reflectivity measured on the sector.

So, for each value of apparent reflectivity it is associated a value of apparent normalized reflectivity obtained in the following way:

$$Z^*(\boldsymbol{x}, h) = \frac{Z(\boldsymbol{x}, h)}{Z(\boldsymbol{x}, h_{ref})} \tag{1}$$

where $\boldsymbol{x}$ and h are the horizontal vector position and the vertical coordinate of the radar measure point, and h_{ref} is the reference height level. The question is that the value $Z(\boldsymbol{x}, h_{ref})$ is unknown and should be obtained by interpolation from the measured values close to the point $(\boldsymbol{x}, h_{ref})$. This need leads to choose the normalization reference level as the minimum height common to all the apparent profiles in the sector, what indeed turns out to be the height of the first PPI at the further limit of the sector. In this way, it can be expected that the radar data around the reference level are not importantly affected by bright band gradients and they reproduce fairly the real values of reflectivity there. If the first PPI intercepts the bright band, a reference level supposed above the bright band should be considered to avoid the strong vertical gradients of the bright band.

Once the values of the apparent normalized reflectivity have been computed, a moving average process of variable width window is applied to obtain the number of points of the mean profile (see Fig. 2).

The resolution of the Mean Apparent VRP is set to a point every 100 m inside and below the bright band, and every 200 m above. The used width of the moving window is 200 m inside and below the bright band, and 400 m above. The different values of resolution and window width above the bright band are necessary because the distribution of the normalized reflectivity values is less uniform there and it has a higher deviation. A first estimation of the bright band limits is then necessary for working with these different values of resolution and width window. It has been done roughly looking for the highest values of normalized reflectivity bright band peak and centering there an interval of 2 km width. Finally the continuity of the MAVPR is achieved by lineal interpolation between the points obtained in the averaging process.

4 Application to data in different sectors

The Mean Apparent Vertical Profile of Reflectivity has been estimated in five annular sectors at the distances between 5

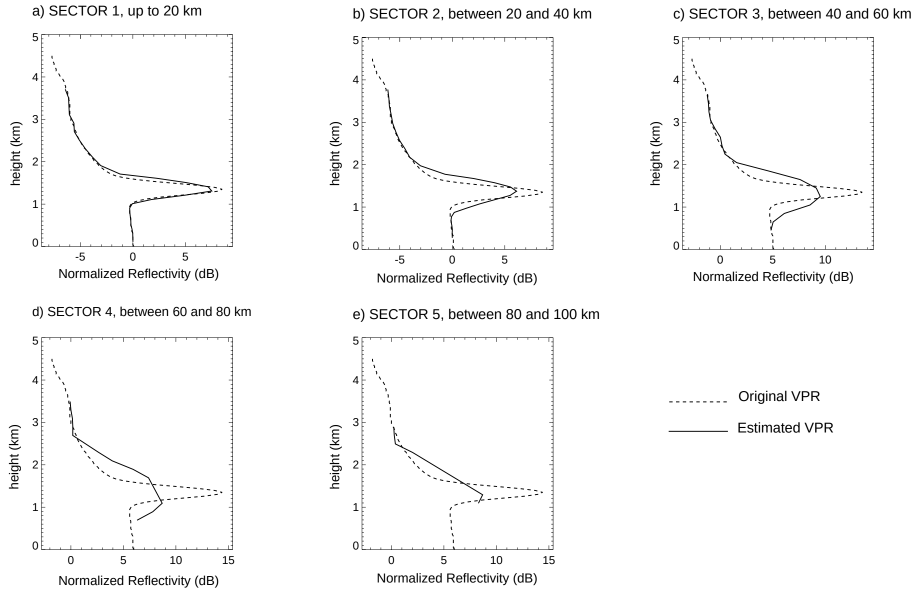

Fig. 3. MAVPR obtained applying the proposed methodology to five annular sectors at different distances from the radar. Each sector has a radial width of 20 km and its azimuthal width is of 30°. The reference height level chosen for the normalization is the minimum height common to all the apparent profiles in the sector, for sectors 1, 2. For sectors 3, 4 and 5, because the height so chosen is affected by the bright band, the reference level has been chosen at a height of 2.5 km on sector 3, and 3 km on sectors 4 and 5).

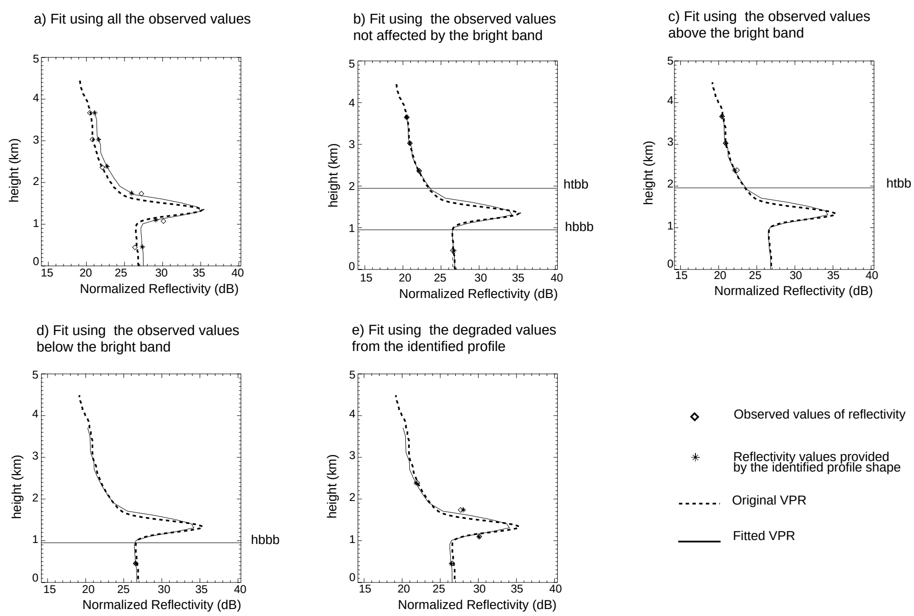

Fig. 4. Estimation of the VPR at one horizontal polar cell in sector 3, at a distance of 41.8 km from the radar. It has been done fitting the estimated MAVPR shape to the observed values. Five procedures are showed, following the two strategies proposed in Sect. 5 (strategy 1 has 4 alternatives, from (a) to (d)).

and 20 km, between 20 and 40 km, between 40 and 60 km, between 60 and 80 km, and between 80 and 100 km. The azimuthal width of each sector is 30°. The results obtained are showed on Fig. 3.

Looking at the graphics showed in Fig. 3 it can be concluded, in agreement with previous studios, that the mean apparent profiles are more corrupted as the distance from the radar increases. This degradation is critical in the zone of the profiles affected by the bright band.

On the other hand while the radar measures of the first elevation do not intercept the bright band, the mean profile reproduces reasonably the original one out of the heights affected by the bright band. However when the first elevation radar data starts to be affected by the bright band, the

MAVPR certainly do not provides good estimates of the original vertical profile. In our case study it happens for sectors further than 70 km from the radar. As a consequence, the proposed methodology identifies the shape of the VPR from the MAVPR estimated in the closest sector (which reproduces quite accurately the original one, see Fig. 3a), and uses this shape to reproduce the VPR at further distances and to improve the estimates of the rain rate at ground.

5 Methodology to estimate the Vertical Profile of Reflectivity (VPR) on each sector using the identified profile shape

As said, we propose to identify the VPR shape applying the MAVPR method explained in Sect. 3 to the sector ranging up to 20 km from the radar. Once the MAVPR has been identified, its shape will be used together with the observed values at any of the other sectors to estimate the rain rate at ground on these sectors. Other authors as Joss and Lee (1995), or Andrieu et al. (1995) prefer to use the profile shape to calculate a correction factor, which allows them to improve the rain rate estimates. However, we suggest that if volume scans are available, the proposed methodology could be an interesting alternative.

So, what we propose is to fit the normalized MAVPR shape to the observed values of reflectivity that correspond to each horizontal polar cell above the ground. In this way, the VPR at any considered point can be estimated multiplying the normalized profile by a fitting factor (the estimate of the reflectivity at the reference height $Z\,(\boldsymbol{x},\,h_{ref})$). The fit could be done in two ways: (1) using directly the values of the estimated mean profile, or (2) degrading the MAVPR (by convolution by the beam pattern) and use the associated values of apparent reflectivity (which represents how the MAVPR will be seen by the radar at a certain distance) for the fitting process.

In the first approach, the degradation of the radar measures because of the beam width could significantly reduced using just the points not affected by the bright band. In order to do this, it is necessary to determine previously the height of the bright band peak, and the heights where the bright band top and bottom are located. This has been done searching on the estimated MAVPR the height for the maximum value of reflectivity (peak of the bright band) and the heights where sharp changes in the profile slope are produced (bright band top and bright band bottom).

In our case study the fit of the non-degraded points of the estimated MAVPR on the observed apparent values has been done analytically by minimum squares, following four alternatives:

(a) using all the observed values (Fig. 4a),

(b) using just the observed values above and below the bright band (Fig. 4b),

(c) using just the observed values above the bright band (Fig. 4c),

(d) using just the points below the bright band, if it is possible (Fig. 4d).

Table 2. Results from applying the identified profile shape to estimate the rain rate at ground. It has been done in five annular sectors at different distances

		Using the first elev. values	Using all the points	Using points above and below the BB	Using points above the BB	Using points below the BB	Using degraded points
SECTOR 1 (5-20 km)	MEAN(error) (dB)	-0.057	-0.143	-0.088	-0.114	-0.063	-0.206
	STDDEV(error) (dB)	0.218	0.131	0.135	0.186	0.196	0.133
	RMSE (dB)	0.225	0.194	0.161	0.218	0.206	0.245
	EFFICIENCY	0.990	0.993	0.995	0.989	0.992	0.988
SECTOR 2 (20-40 km)	MEAN(error) (dB)	-0.175	0.116	-0.017	-0.006	-0.050	-0.216
	STDDEV(error) (dB)	0.237	0.324	0.156	0.180	0.254	0.105
	RMSE (dB)	0.294	0.343	0.156	0.180	0.259	0.240
	EFFICIENCY	0.992	0.990	0.998	0.997	0.994	0.995
SECTOR 3 (40-60 km)	MEAN(error) (dB)	-0.002	0.189	0.153	0.105	0.206	-0.168
	STDDEV(error) (dB)	0.321	0.594	0.179	0.166	0.350	0.111
	RMSE (dB)	0.321	0.623	0.235	0.196	0.405	0.202
	EFFICIENCY	0.981	0.931	0.990	0.993	0.971	0.993
SECTOR 4 (60-80 km)	MEAN(error) (dB)	1.995	1.459	0.321	0.321	X	-0.182
	STDDEV(error) (dB)	0.924	0.366	0.470	0.470	X	0.371
	RMSE (dB)	2.198	1.504	0.569	0.569	X	0.413
	EFFICIENCY	0.586	0.806	0.972	0.972	X	0.985
SECTOR 5 (80-100 km)	MEAN(error) (dB)	3.182	-0.816	0.202	0.202	X	-0.121
	STDDEV(error) (dB)	0.418	1.180	0.322	0.322	X	0.392
	RMSE (dB)	3.209	1.433	0.377	0.377	X	0.409
	EFFICIENCY	0.273	0.855	0.975	0.975	X	0.988

This methodology has been applied in the five sectors defined in Sect. 3, fitting the VPR for any horizontal polar cells centered in each azimuth and radial value of the volume scan.

The results (see Table 2) are analysed in terms of the errors between the rain-rate at ground provided by the fitted profile and the one corresponding to the original rainfall field. These results show that the proposed methodology systematically provides better estimates of the rain rate at ground than those obtained using directly the lowest scan values. These estimates show lower RMSE and higher efficiency on all the sectors, but especially on the two furthest from the radar (sector 4, between 60 and 80 km; and sector 5, between 80 and 100 km), where the first elevation is affected by the bright band. As values below the bright band are not observed on these both sectors, the fit can only be done using alternatives (a) or (c) (alternative (d) is not possible and (b) turns out to be identical to (c)). The last procedure is which leads to better results.

On the nearest sectors the proposed methodology slightly improves the estimates by the first elevation values, if the points non-affected by the bright band are used (i.e. alternatives (b) to (d)). The improvement is lower than in the further sectors because at these distances the bright band does not affect the first elevation values, and they provide quite good estimates.

Therefore, the best alternative for this first approach is to fit the VPR by using just the observed apparent values non affected by the bright band, which near the radar are the points above and below (alternative (b)) whereas in the furthest sectors only the points above the bright band can be used (alternative (c)).

The second proposed approach consists on simulating the radar measures of the MAVPR when it is placed at different distances from the radar. To do it, the MAVPR is convolved by the beam, then the degraded MAVPR values are compared to the observed apparent ones and a fitting parameter is obtained, which in fact is the value to multiply by the normalized profile to obtain the estimated VPR at that point. This local VPR will allow us to estimate the rain-rate at ground (extrapolated from their lowest value). Looking at Table 2 it could be noted that this procedure gives the best estimates of the rain rate at ground for the sectors further than 40 km from the radar (sector 3, between 40 and 60 km; sector 4, between 60 and 80 km; and sector 5, between 80 and 100 km), together with the proposed alternative from the first approach (alternative (c)). However, even if from our results the second approach could be thought as more accurate, it is more time consuming. So probably, in the case of an operational application the first one, using just the points above the bright band, could be the most interesting one.

6 Conclusions

In this paper a methodology to identify the shape of the Vertical Profile of Reflectivity from radar data and to estimate the rainfall at different distances has been proposed. The identification of the profile shape consists on estimating the Mean Apparent VPR (MAVPR) in the nearest sector to the radar. If radar volume scans are available, the apparent reflectivity measurements in this sector cover lowest heights with enough resolution and, on the other hand, they are practically not affected by the smoothing effect due to the beam width. So, the shape of the VPR could be estimated accurately. Once the MAVPR shape has been obtained near the radar, it is fitted to the apparent reflectivity values measured at different ranges to estimate the rainfall at ground.

The results of applying the proposed methodology in a simple simulation environment show that it improves the estimates provided by the lowest elevation scan considerably. Among the tested alternatives, the best fits are obtained either when the points affected by the bright band are not considered, or when the MAVPR estimated in the first sector is degraded (convolved by the beam pattern) before fitting it at a certain distance. However, even though the performance of both procedures is similar, the simplicity of the first one makes it more suitable from an operational point of view.

The improvement of the estimates provided by this methodology are due to its ability to solve the critical situation produced when the first elevation intercepts the bright band at further distances from the radar (what cause an important overestimation of the rain- rate if it is estimated from the first elevation observed values).

Its main limitations consist on the imposed spatial homogeneity of the vertical profiles and on the required presence of significant rainfall field close to the radar. However, in the case of no rain on the closest sector, radar data from the second sector could be still useful to estimate the MAVPR and to use it to estimate the rain-rates at ground at further distances.

Future work will focus on the improvement of the proposed methodology for non-uniform VPR data, and further tests in the case of no precipitation near the radar.

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