3D radar reflectivity mosaics based on a variational method

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1. Introduction

Dense radar networks allow getting better Quantitative Precipitation Estimates (QPE) than those obtained with individual radars. Not only taking the advantage of a larger coverage but improving quality of rainfall estimates in overlapping areas as well. Well-known sources of error as attenuation by intense rainfall or errors associated with range can be mitigated through radar mosaics. So far mosaics obtained in radar networks are usually built by selecting the estimate from one of the radars at each grid point. This selection is done with criteria such as the maximum observed value (as an attempt to compensate for strong attenuation and beam blockage) or the observation from the closest radar (which considers the distance to the radar as the main error-driving factor). Other options have been presented in the literature as the criterion of minimum distance to Earth surface (Michelson et al. 2000) or mosaics based on quality indices (Fornasier et al. 2006; Peura and Koistinen 2007). Zhang et al. (2005) proposed a weighted average based on the distance to each radar for constructing three-dimensional reflectivity mosaics.

In this study, we propose an alternative mosaicking technique to deal with sources of error as beam broadening or signal attenuation by precipitation in a simulation framework. A model that simulates how radars measure the precipitation field can be established using the radar equation together with the particular characteristics of the radar. Following the concept of an inverse method, we propose to construct a model for each radar of the network pointing to the same area, and to retrieve the most realistic field constraining by the multiple observations. The methodology is based on the minimization of a cost function that penalizes the discrepancies between the simulated and actual observations for each radar.

The methodology has been applied on two radars close to Barcelona (Spain). In addition, we carried out a verification using observations recorded with an independent radar not included in the mosaicking methodology.

2. Data used

The radar data used in this study to generate radar reflectivity mosaics were recorded with two radars of the Meteorological Service of Catalonia (SMC). These are C-band radars located 72 km apart, in the summit of la Miranda and the Creu del Vent hill (we will refer to them as LMI and CDV). Both radars follow a scanning strategy of 16 elevations with a resolution of 1 degree in azimuth and 1 km in range. The maximum range of the CDV radar is 150 km while for LMI radar is 130 km. Complete volume scans are produced every 6 minutes for both radars.

An independent radar belonging to the Spanish National Meteorological Agency (AEMET) has been used to carry out a preliminary verification of the methodology. It is a C-band radar located in the Puig d’Agulles hill (close to Barcelona) and we will refer to it as the BAR radar. It is located 45 km from the CDV radar and 90 km from the LMI radar. The BAR radar has a scanning strategy of 19 elevations and a maximum range of 120 km. Scans have a resolution of 0.8 degrees in azimuth and 1 km in range.

Two different case studies have been selected to apply the proposed methodology. The first one is a convective situation occurred on 02 November 2008 at 0330 UTC. In this case the presence of strong convective cells allows to study the performance of the methodology when the effects of attenuation by intense rain are evident. The second case corresponds to a widespread situation recorded on 4 February 2010 at 1430 UTC, with the presence of the bright band peak at about 2 km.

Radar data of both cases have been processed to remove ground clutter and mitigate the effect of beam blockage. By doing so we intend to consider only meteorological echoes. Radar data have also been adjusted with precipitation estimates of a raingauge network for a long period in order to partially compensate for possible miscalibration of the radars.

Three-dimensional mosaics are generated in a Cartesian grid of 95 x 75 x 7 km$^3$ with a grid spacing of 250 meters in the vertical direction and 500 m in the horizontal directions. The area covered by the grid includes the three radar locations (Figure 1).

3. Existing mosaicking techniques

Two 3D compositing methods have been used as a reference to compare the results of the proposed methodology:

3.1 Maximum value technique (M1)

In a first step, observations of both LMI and CDV radars are converted form polar coordinates to the 3D common Cartesian grid mentioned in Section 2. Such conversion is done with the nearest neighbor algorithm, which preserves extreme values and small-scale variability (Trapp and Doswell 2000). Then the maximum value in each point of the grid is selected. The maximum value technique is widely used in operational context for 2D composites.
3.2 Distance-weighted mean (M2)

Zhang et al. (2005) proposed a 3D composition scheme for the WSR-88D network based on the requirements of realistic representation of convective-scale features of rainfall and a low computational cost. For remapping polar radar data to Cartesian coordinates, they decided to use vertical interpolation for convective storms and for widespread precipitation both vertical and horizontal interpolation. The proposed methodology is based on a distance-weighted mean to compose measurements from different radars at each grid point.

4. Methodology

4.1 Minimization of a cost function

The methodology is based on the minimization of a cost function that penalizes discrepancies between actual observations and simulations of the radar sampling performed over the retrieved field. We define the cost function as:

$$J(\mathbf{z}) = \left\| dB[Z_{\text{LMI}}] - dB[\hat{Z}_{\text{LMI}}(\mathbf{z})] \right\|^2 + \left\| dB[Z_{\text{CDV}}] - dB[\hat{Z}_{\text{CDV}}(\mathbf{z})] \right\|^2$$  \hspace{1cm} (1)

Where $\mathbf{z}$ is the retrieved high-resolution 3D reflectivity field, $Z_l$ is the reflectivity volume observed with the $l$ radar ($l \in \{\text{LMI, CDV}\}$), $\hat{Z}_{l,m}(\mathbf{z})$ is the simulated reflectivity volume scan for the $l$ radar (see Section 4.2), $dB[\bullet]$ is the operator $10 \log[\bullet]$ and $\left\| dB[Z_l] - dB[\hat{Z}_{l,m}(\mathbf{z})] \right\|$ stands for the Euclidean distance between observations and simulations.

The cost function is minimized iteratively with a conjugate gradient method to retrieve the 3-dimensional mosaic, using as a first guess the mosaic obtained with method M2 (see Section 3.2).

4.2 Simulation of the radar sampling of the atmosphere

Simulations have been carried out using a model that reproduces the radar sampling of the atmosphere considering the characteristics of the radar (location, beam width, pulse length, scanning strategy...), power distribution within the radar beam and attenuation by precipitation, similarly as in Llort et al. (2006).

Given a 3-dimensional reflectivity field, a complete volume scan is generated with the model. The simulation model is based on the radar equation and the propagation of the radar beam is assumed to follow the 4/3-effective Earth radius model (Doviak and Zrnic 1992). For a certain elevation angle and certain azimuth, Equation 2 expresses the reflectivity simulated at range $r$, $\hat{Z}_m(z, r)$ as a function of the high-resolution 3D reflectivity field $z$:

$$\hat{Z}_m(z, r) = \tilde{Z}(z, r) \cdot \exp[-0.46 \int_0^r \alpha \cdot \tilde{Z}(s, z) ds ]$$

\hspace{1cm} (2)

Where $\tilde{Z}(z, r)$ is the intrinsic (unattenuated) reflectivity at range $r$ (smoothed following the power distribution within the beam), $\alpha$ and $\beta$ are the parameters of a power law relationship between specific attenuation and reflectivity ($k = \alpha Z^\beta$), $V(r)$ is the radar sampling volume at range $r$, $\left\| W \right\|^2$ is the range weighting function (in this model the function proposed by Doviak and Zrnic (1992) is used), $f^2$ is the normalized power which is approximated with a Gaussian function.

This equation allows to reproduce the effect of beam broadening, the effect of the power distribution within the beam and signal attenuation by precipitation.

5. Results

The methodology has been applied to LMI and CDV radars for the two cases described in Section 2.

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Figure 1. Illustration of radar locations and domain. Locations of LMI, CDV and BAR radars are shown in a topographical map of NE Spain (near the city of Barcelona). The rectangle indicates the area of the domain.
5.1 Case 02 November 2008 0330 UTC

The retrieved 3-dimensional reflectivity field for this convective case is presented in Figure 2. Figures 2a and 2b show that a good part of the domain is covered by precipitation with several convective cells embedded. The vertical development of convective cells A and B is shown in vertical cross sections of Figures 2c and 2d – cell A reaches up to 5 km height while B overpasses 6 km height.

![Figure 2](image)

**Figure 2.** CAPPIs and vertical cross sections of the 3-dimensional reflectivity mosaic retrieved with the variational method from radar observations measured at 0330 UTC on 2 November 2008. The CAPPIs correspond to heights of 2 and 3 km [(a) and (b), respectively] and vertical cross sections (c,d) are indicated in the CAPPIs with red straight lines, line P-P’ (c) and line Q-Q’ (d). The thin black lines on the panels correspond to the path of the radar ray for each elevation. Gray areas correspond to regions without radar observations (in altitudes below 1 km) or without retrieved values (in higher altitudes). A and B indicate two intense convective cells.

To qualitatively assess the performance of the method, Figure 3 shows actual and simulated observations for the LMI radar at the elevation of 0.5°. Simulated observations have been performed over the mosaics generated with the different compositing techniques (M1, M2 and variational method). All simulations have been performed using Equation 2.

Visual comparison of Figures 3a and 3d show remarkable resemblance between observations and simulations for the LMI radar. Simulations computed over the M1-mosaic (Figure 3b) and the M2-mosaic (Figure 3c) show discrepancies with respect to observations. For instance, the highest observed reflectivity values in convective cells (Figure 3a) are reproduced in Figure 3d but not in Figures 3b or 3c. Also, the attenuation corridor labeled as C is quite better reproduced in Figure 3d than in Figures 3b or 3c.

Figure 4 shows that similar conclusions can be made for the comparison between observations and simulations for the CDV radar: The simulations over the mosaic obtained with the variational method are more similar to the observations than the other ones, in particular the extreme values in cell B are better reproduced.

5.2 Case 04 February 2010 1430 UTC

The mosaic obtained for this case is shown in Figure 5. The 1.5-km and 2-km CAPPIs (Figures 5a and 5b) show quite uniform fields as expected in a widespread case. The latter shows higher reflectivity values than the former because it corresponds, approximately, to the height of the bright band peak. This can be confirmed with the vertical cross sections (Figures 5c and 5d) and their mean vertical profile of reflectivity (VPR).

Simulations over the retrieved field reproduce remarkably well the observations, as shown in Figure 6. In particular, the traces of the bright band are well defined for both radars.

6. Verification

In the case of 02 November 2008 0330 UTC, observations of the BAR radar were available, so we can assess the performance of the mosaicking methodology using an independent source of information. To do this, the radar measurement
model has been applied for the BAR radar over the 3-dimensional mosaic obtained using only LMI and CDV observations. Then these simulations are compared with actual BAR observations. Figures 7a and 7d show the remarkable resemblance between observations and simulations. Simulations over mosaics obtained with the reference methods M1 and M2 have also been computed and shown in Figures 7b and 7c respectively. The main differences between such simulations and observations are the signal extension beyond the central convective cell in the M1-simulation and that the M2-simulation do not achieve the high values of reflectivity observed in convective cells.

![Figure 3](image3.png)

**Figure 3.** Reflectivity field of the 0.5° elevation observed with the LMI radar on 2 November 2008 at 0330 UTC (a) and reflectivity fields corresponding to the simulation of the 0.6° elevation for the LMI radar over the mosaics obtained with the technique M1 (b), M2 (c) and the variational method (d). LMI radar location is indicated with a star. White means no rain. Shaded areas in the observation and gray areas in simulations are not included in the domain. Coordinate axis indicate Easting (x) and Northing (y) distance to the radar. Label C shows the effects of attenuation by an intense convective cell (a) and its reproductions (b,c,d).

![Figure 4](image4.png)

**Figure 4.** Same as Figure 3 but for the CDV radar.
Figure 5. CAPPIs and vertical cross sections of the 3-dimensional reflectivity mosaic retrieved with the variational method from radar observations measured at 1430 UTC on 4 February 2010. The CAPPIs correspond to heights of 1.5 and 2 km [(a) and (b) respectively] and vertical cross sections (c, d) are indicated in the CAPPIs with red straight lines, line P–P’ for x=20 km (c) and line Q–Q’ for y=50 km (d). On the right of the vertical cross sections there is the mean vertical profile of reflectivity (VPR) of the corresponding vertical cross section, that is, for each height the mean reflectivity value of the cross section is represented. The thin lines on the panels correspond to the path of the radar ray for each elevation. Gray areas correspond to regions without radar observations (in altitudes below 1 km) or without retrieved values (in higher altitudes).

Figure 6. Reflectivity field of the 2.9° and 3.9° elevation observed with the LMI (a) and CDV (b) radar respectively on 4 February 2010 at 1430 UTC and reflectivity fields corresponding to the simulation of the same elevations over the mosaics obtained with the variational method (c,d). Radar location are indicated with a star. White means no rain. Shaded areas in the observation and gray areas in simulations are not included in the domain. Coordinate axis indicate Easting (x) and Northing (y) distance to the radar.
7. Conclusions

The results presented above show that the 3-dimensional reflectivity mosaics obtained in this work are compatible with the different observations recorded with two different radars assuming the model for the radar sampling of the atmosphere (Section 4.2). The retrieved fields reproduce coherent features as the vertical development of convective cells or the reflectivity enhancement of the bright band, as shown for two significantly different examples. Qualitative comparison between observations and simulations shows a significant improvement in compared to what is obtained with other existing mosaicking methods.

A verification test has been carried out using observations recorded with an independent radar. Simulations over the retrieved field show better agreement with observations than simulations over mosaics obtained with other methods. This is a positive first step to the validation of the methodology whose final goal is to generate better mosaics for QPE.

Thus, for next advancements, a more quantitative and systematic verification is being carried out using independent radar information, but also carefully comparing retrieved fields with precipitation estimates from a raingauge network.

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