

## Monitoring Extreme Rainfall Events in an Alpine Region Using Two C-Band Radars and a Network of Gages

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### 1. Introduction

It is well known that radar rainfall measurements suffer from several types of errors, mainly caused by the need to transform measurements made aloft to the corresponding surface rainfall value (note that this includes the Z-R relationships). Errors caused by ground clutter or its suppression, lack of visibility and beam broadening with distance are probably the dominant error for operational radar, especially in Alpine regions. To reduce these errors, *Gabella et al.* [1999] proposed the joint use of a texture-based algorithm for ground clutter suppression and of a Weighted Multiple Regression (WMR) method for radar-network of gages adjustment. The suppression algorithm is applied off-line, after all other available methods of clutter removal have been used. Then the WMR technique allows to correct each radar pixel value as a function of three explanatory variables: the distance from the radar, the height a meteorological target must reach to be visible from the radar site, and the ground height. The aim of the present study is a validation of the data of two C-band radars having a large area of common coverage using the WMR method between the two radars as well as among radar and rain-gages. In the second comparison (Sec 5.1), the radar-gages data pairs are subdivided in two mutually exclusive groups: one is used for training, the other for testing, and vice versa. To compare the two radars (Sec.5.2), the radar-gages data pairs are used for training. Then precipitation estimates derived from two radars are directly compared on a  $2 \times 2$  km<sup>2</sup> grid within an approximately 10000 km<sup>2</sup> area of common coverage leading to 2500 values for the validation.

The meteorological event used for this preliminary validation is the November 1994 Piemonte-flood. The ground instrumentation includes 66 rain gages and 5-minute maximum reflectivity maps acquired by an old non-coherent radar and a new generation" Doppler one.

### 2. Study Area Description

The area concerned is located in northwestern Italy. It is a partly flat and partly hilly land surrounded by high mountains (Appennino Ligure and the Alps) in every but the East direction. 66 rain gages were available during the entire flood period; they are located within the Piemonte-district (approximately 25000 square kilometer). The Regione Piemonte C-band radar lies on a small chain of hills, surrounded mainly by flatlands. It is located on the top of Bric della Croce at 710 m a.s.l., just 5 km East of Torino. The Swiss C-band radar is located on the top of Monte Lema at 1625 m a.s.l. Radar-gages distances are considerable for the Italian radar and even larger for the Swiss: for the first radar the average distance is 72 km with 35 km standard deviation; for the second one it is 135 km and the standard deviation is 56 km. The Ground Echo Characterization Software (GECS - a computer code for radar site assessment) [*Gabella and Perona*, 1998] has been used to compute the minimum Height of Visibility for both radar sites ( $HV_{\min}$  is the height for which the beam axis is just touching" the horizon). The equivalent-earth 抐-radius used is 8500 km (see next Section). For Bric, the average value of the minimum height over the 69 gauges is 1180 m with 1010 m standard deviation. For Lema, the average value is 1330 m with 1210 m standard deviation.

### 3. Instrumentation and Data Description

The meteorological network of the Regione Piemonte is equipped with tipping-bucket rain gages; data are recorded every ten minutes (0.2 mm resolution) and transmitted in real time to the operation center. As far as the radars are concerned, Monte Lema radar is a "3<sup>rd</sup> generation" Doppler radar, scanning the full volume in 5 min with a 1° beam (20 elevations). Only clutter-free range bins (1°×1°×80 m) are averaged and resampled on a 1×1 km Cartesian grid. At the time

of the flood (November 1994), Bric was sampling 14 elevation steps of  $1.5^\circ$  in 5 min. The raw radar data were averaged over four range-bins of  $1.5^\circ \times 1.5^\circ \times 250$  m and resampled on a Cartesian kilometric grid ( $1 \times 1$  km pixel size). During November 1994 a planimetric projection of maximum reflectivity values over the entire columnar volume were recorded by both radars. Because at the time of the experiment the Bric radar was non-coherent, clutter rejection was performed only by applying a stored clutter map. For the Lema Doppler radar, a more complex approach for clutter suppression using 7 tests on the radar return was being developed [Joss and Lee, 1995]. A texture-based" technique for the removal of residual ground clutter was applied to both radars data: Bric radar absolutely needed it while for Lema its decision-tree had already eliminated most of the clutter [Gabella and Perona, 1997]. As shown by Gabella et al. [1999], effective clutter suppression is needed before applying regression-based correction technique, especially when weighing the samples in the regression with the radar-derived precipitation amounts.

The disastrous precipitation flooding the Southern Piemonte area in November 1994 was associated with heavy rain in relatively small areas. The most intense rain occurred in the second half of November 4 to midnight of November 5. Widespread precipitation, although not as intense as on the previous day, occurred also on November 6 over a wide portion of the region. The radiosondes sampling (every 12 hours in *Milano Linate*) show a standard value of the refractivity gradient in the boundary layer (equivalent-earth's-radius ranging from 8000 to 8850 km) and a height of the zero isotherm between 2700 and 3000 m a.s.l. This analysis is based on data between 1600 UTC of November 4 and 0800 UTC of November 6. Cumulative precipitation amounts of all gages during these 40 hours of observation spanned from 36 mm to 439 mm. The average is 151 mm (92 mm standard deviation). The Bric radar detected no echo above 6 gages (northern gages, distances ranging from 126 to 163 km), the Lema radar above 12 gages (southwestern gages, distances ranging from 170 to 226 km): hence the radar-gage comparisons (Sec. 5) uses 60 gages for the Bric radar, 54 gages for the Lema radar. The reflectivity of each clutter-free radar pixels has been converted to precipitation rate using a power-law Z-R relationship with  $b=1.5$  and  $a=316$ , as derived by Doelling et al. [1998]. All clutter-free samples of the 4 radar pixels closest to the gage were selected and averaged before the comparison.

#### 4. The Weighted Multiple Regression Method

Let us define the Assessment Factor (AF) for each radar-gage data pair as the ratio between the integrated radar-derived rain-amount and the corresponding integrated gage amount. In this experiment the integration period has been chosen coincident with the observation period (40 hours) in order to reduce bias errors and fluctuations of the AF. E.g. Kitchen and Blackall [1992] show the large scatter of instantaneous values for a given location of the two types of instruments (radars and gages) caused by differences in sampling modes. Therefore, in many cases and certainly for hydrological purposes, it is necessary to integrate in time [e.g. Collier, 1986].

The basic idea of the WMR method is that the variability of the AF could be explained" in terms of the following three independent variables:

- D, radar-gage Distance (significant because it reflects effects caused by beam-broadening);
- $HV_{\min}$ , minimum Height of (radar) Visibility above the gage (reflects beam-shielding);
- HG, Height of Gage (reflects precipitation growth related to orography).

Obviously, the vertical profile of reflectivity (including the bright band) complicates the analysis. Here, a weighted multiple regression reflects in part its influence and, therefore, corrects the radar estimates. The following procedure is used:

1) Data are integrated over the whole observation period to reduce fluctuations of the AF (dependent variable). For each  $j^{\text{th}}$  radar-gage data pair,  $AF_j = R_j/G_j$  has been computed,  $R_j$  being the total radar-derived cumulative amount,  $G_j$  the corresponding amount recorded by the gage.

2) Data are transformed into the logarithmic dimension to allow optimum performance of a linear regression. Since the Z-R relationship and the range dependence of the radar signal follow power-laws,  $\text{Log}(AF)$  and  $\text{Log}(D)$  are regressed.  $\text{Log}(AF)$  has also the advantage of being symmetric with respect to R and G. If the vertical reflectivity profile decreases logarithmically with height,  $\text{Log}(AF)$  is linearly related to HV and HG.

3) To obtain the regression coefficient, the sum of the squares of the residuals is minimized. However, for best results, the residuals must be weighed according to the physical quantity of interest, that is the rainfall. Evidently, there are two possibilities, either the weights are the total radar-derived precipitation amounts ( $W=R$ ) or the total amount of rain measured by the gages ( $W=G$ ).

4) Finally, the regression coefficients are used to estimate  $\text{Log}(AF)_{\text{est}}$  for each pixel of the area covered by the radar.  $\text{Log}(AF)_{\text{est}}$  allows to calculate

the ratio  $R/AF_{est}$  to obtain the corrected rain field.

It is worth noting that the bright band is implicitly included in the coefficients of this procedure, being part of the vertical profile of reflectivity. This approach may seem crude, but for the complex Alpine orography a finer procedure is not available so far. In a column matrix form, the multiple linear regression can be written as:

$$AF_{est}(dB) = a_0 + a_D \log(D) + a_{HV} HV + a_{HG} HG, \quad (1)$$

where the components of the vectors are  $AF_j = R_j / G_j$ ,  $D_j$ ,  $HV_j$ ,  $HG_j$ , where  $j$  identifies the  $j^{th}$  rain-gage.

A description of the statistics of the quantities used in the regression analysis for both radars can be found in Gabella et al. [1999]. Here, for validation purposes, the whole data set (54 data-pairs for Lema, 60 for Bric) is subdivided into two mutually exclusive subsets (see Sec. 5.1): if the first one is used as training data set to derive the multiple regression coefficients, then the second one provides the data to be corrected with the regression obtained in the first step, and vice versa. The coefficients derived from the whole data-set, coming from twice as many data-pairs (therefore being more robust), are used in the radar-radar-comparison (Sec. 5.2): in this case 2291 radar-radar data pairs provide the data to be corrected for validation purposes.

As far as Monte Lema radar is concerned, Table 1 shows the value of the coefficients of the regression (Eq. 1) using the total radar derived precipitation as weights ( $W=R$ ). The values of the coefficients with the other two kind of weights (equal weight: ( $W=1$ ); weight is the total amount of rain measured by the gage: ( $W=G$ )) are similar (slightly larger in absolute value) and are not presented for the sake of concision. Values are given for all data as well as for the two mutually exclusive subsets. As expected, both  $a_D$  and  $a_{HV}$  are always negative, indicating that the radar underestimates rain for larger distances and for higher sampling volumes.

The value of the coefficients of the weighted multiple regression for the Bric radar are shown in Table 2 (again, only the case  $W=R$  is presented). This radar too, underestimates rain for larger distances and for higher sampling volumes.

## 5. Results

### 5.1. Radar-Gages Comparison

Here, the difference in precipitation estimates between radar and gage, i.e. the error vector ( $R-G$ ), is considered. Its characteristics are summarized in the first two principal moments: the mean

Data-set type		$a_0$	$a_D$	$a_{HV}$	$a_{HG}$
Whole (54 gages)		21	-1	-4.	+
		.1	1.6	0	0.8
I Subset (27 gages)		15	-	-5.	+
		.9	9.1	1	1.9
II Subset (27 gages)		21	-1	-4.	+
		.9	2.3	1	2.0

**Table 1.** Coefficients resulting from the WMR (Eq. 1) for Lema radar data; weights are the total radar-derived rain heights ( $W=R$ )

Croce radar					
Data-set type		$a_0$	$a_D$	$a_{HV}$	$a_{HG}$
Whole (60 gages)		22	-1	-3.	+
		.4	6.6	3	0.5
I Subset (30 gages)		21	-1	-3.	+
		.2	5.7	1	0.6
II Subset (30 gages)		23	-1	-2.	-
		.0	6.7	4	2.2

**Table 2.** Same as Table 2 but for the Bric della

value,  $\text{mean}(R-G)$ , and the standard deviation,  $\text{std}(R-G)$ . For ease of comparison, they are normalized to the sum of the mean precipitation measured by both, leading to the normalized Mean areal precipitation difference ( $n\text{Mapd}$ ) and to the normalized Spread areal precipitation difference ( $n\text{Sapd}$ ):

$$n\text{Mapd} = \text{mean}(R-G) / [\text{mean}(R) + \text{mean}(G)], \quad (2)$$

$$n\text{Sapd} = \text{std}(R-G) / [\text{mean}(R) + \text{mean}(G)]. \quad (3)$$

Obviously, the correction procedure based on WMR is meaningful only if both  $n\text{Mapd}$  and  $n\text{Sapd}$  become smaller after the adjustment. Raw and corrected radar estimates are compared with the gages for an independent data-set (for the 1<sup>st</sup> subset when coefficients derived from the 2<sup>nd</sup> subset are used to correct radar estimates, and for the 2<sup>nd</sup> subset when the coefficients derived from the 1<sup>st</sup> sub-set were used). The last two columns of Table 3 show the normalized mean of areal precipitation differences and the normalized spread of areal precipitation differences for Monte Lema radar before and after the correction based on WMR. The spread of the errors decreases only if the observations are weighed with the radar-derived precipitation values (the mean underestimation is reduced in any case). For Bric della Croce radar (Table 4), too,  $W=R$  gives the best results, but even

Type of data	Dat a-set	nMapd (Eq. 2)	nSapd (Eq. 3)
Raw data	I	-0.64	0.52
	subset		
postWMR (W=1)	I	+0.52	1.36
	subset		
postWMR (W=G)	I	+0.43	1.03
	subset		
postWMR (W=R)	I	-0.12	0.36
	subset		
Raw data	II	-0.58	0.50
	subset		
postWMR (W=1)	II	-0.03	0.31
	subset		
postWMR (W=G)	II	+0.02	0.27
	subset		
postWMR (W=R)	II	-0.06	0.37
	subset		

**Table 3.** Normalized Mean and Standard deviation of the areal precipitation difference between Monte Lema Radar and Gauges

Type of data	Dat a-set	nMapd (Eq. 2)	nSapd (Eq. 3)
Raw data	I	-0.66	0.52
	subset		
postWMR (W=1)	I	+0.04	0.49
	subset		
postWMR (W=G)	I	+0.13	0.61
	subset		
postWMR (W=R)	I	-0.01	0.45
	subset		
Raw data	II	-0.66	0.63
	subset		
postWMR (W=1)	II	+0.13	0.53
	subset		
postWMR (W=G)	II	+0.16	0.59
	subset		
postWMR (W=R)	II	-0.23	0.33
	subset		

**Table 4.** Same as Table 3 but for the Bric della Croce radar

a simple multiple regression (W=1) improves the situation.

### 5.2. Radar-Radar Comparison

Here, the difference in precipitation estimates between Bric radar ( $R_B$ ) and Lema ( $R_L$ ) radar are considered. Again, the characteristics of the error vector are summarized in terms of Mean value and Standard deviation normalized to the sum of the

mean precipitation measured by both radars, namely:

Type of data	nMapd (Eq.4)	nSapd (Eq. 5)
Raw data	0.27	0.76
postWMR (W=1)	0.09	0.29
postWMR (W=G)	0.08	0.29
postWMR (W=R)	0.06	0.25

**Table 5.** Normalized Mean and Standard deviation of the areal precipitation differences between Bric Radar and Lema Radar

$$nMapd = \text{mean}(R_B - R_L) / [\text{mean}(R_B) + \text{mean}(R_L)], \quad (4)$$

$$nSapd = \text{std}(R_B - R_L) / [\text{mean}(R_B) + \text{mean}(R_L)]. \quad (5)$$

The comparison between radar estimates was limited to a common area" where both radars can perform in a sensitive" way: the estimated value of the AF (in dB) through WMR coefficients was chosen to be greater than -9 dB. The total common area" for the comparison contains 9548 km<sup>2</sup>. Due to the high variability of radars azimuthal resolution within the common -9 dB region, 4 radar pixels are averaged (as in the comparison with the gages, see Sec. 3): hence we have 9548/4 radar derived precipitation values in the  $R_B$  (Bric) and  $R_L$  (Lema) maps (matrices). The last two columns of Table 5 show the normalized mean of areal precipitation differences and the normalized spread of areal precipitation differences between the two radars before and after the correction based on WMR (different type of Weights). Thanks to the correction based on WMR, it is possible to reduce both the mean error and, most of all, its standard deviation. As in the radar-gages comparison (Sec 5.1), best results are obtained if the observations are weighed with the radar-derived precipitation values (W=R).

## 6. Conclusions

Thanks to a Weighted Multiple Regression (WMR) method for radar- gages adjustment, it has been possible to retrieve a two-radars-derived quantitative distribution of precipitation fields for the November 1994 flood event even in an Alpine region notwithstanding its complex orography. The WMR correction technique was developed in such a way to successfully reduce the macroscopic biases" related to distance, height of visibility and orography. In fact, we find that:

- for both, the old non-Doppler and the Doppler radar, the correction scheme based

on .multiple regression significantly reduces the Mean Error;

- if the observations are weighed with the radar-derived precipitation values, the error standard deviation decreases significantly. The weights in the regression act as soft” thresholds, eliminating the sometimes difficult task to decide if the radar-gauge data pairs are significant (and consequently, acceptable);
- the two radars show quantitative comparable results in the rain distribution only after applying the correction procedure based on the weighted multiple regression;
- in a region of about 10000 km<sup>2</sup> surrounding Torino, thanks to the WMR correction technique, the normalized mean (pixel-by-pixel) error between the two radars is reduced from 27% to 6%, the normalized standard deviation from 76% to 25%.

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