# CHARACTERIZING A WEATHER RADAR PROPAGATION ENVIRONMENT TO IMPROVE REMOTELY SENSED PRECIPITATION MEASUREMENTS

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**Abstract**

*A physically-based method to reduce the macroscopic "biases" related to the propagation environment of a weather radar in mountainous and hilly regions is here presented. It is based on a non-linear, weighted multiple regression scheme, which separates the influences of the calibration, beam-broadening with distance, beam shielding and orography by calculating four correction coefficients that lead to the best agreement with the available in situ measurements. Once the regression coefficients have been determined, the complete map of correction factors (for the given radar site, orography and mean atmospheric refraction) can be calculated and applied to the whole radar-derived precipitation field map. The performances of the method using daily integration periods are presented for the disastrous October 2000 Piedmont flood.*

## 1. INTRODUCTION

The sources of error in the radar estimation of rain intensity on the ground can be divided into three broad categories: (A) the electronic stability of the radar system (repeatability is more important than absolute calibration for rainfall estimation [1]); (B) the "radar propagation environment", i.e. questions related to the beam geometry-beam diagram, beam broadening with distance, clutter, anomalous propagation, visibility effects, i.e. earth curvature and, most of all, screening by orography [2]; (C) the fluctuations of atmospheric conditions, i.e. the spatio-temporal variability of the vertical reflectivity profile, the attenuation and questions related to the micro-physics of precipitation (including non homogeneity of rain [3]). We describe here an approach that has been developed in cooperation with MeteoSwiss [4] to reduce the macroscopic "biases" related to the "radar propagation environment". The method is based on a non-linear, weighted multiple regression scheme, which tries to explain the spatial variability of the "errors" that affect radar precipitation estimates (in comparison with *in situ* measurements). This method separates the influences of: 1) calibration, 2) beam broadening with distance, 3) visibility (partial beam occultation and shielding by orography) and 4) orographic effects. A non-linear, weighted multiple regression (WMR) is used to calculate the four coefficients that lead to the best agreement with the available *in situ* measurements. Once the regression coefficients have been determined using a set of measurements, the verification is performed using a different, independent data set of remotely sensed and *in situ* measurements. The method has so far been extensively applied, and successfully verified, as an "after-the-fact" adjustment, that is, the tuning and the corrected precipitation field was computed and estimated for the same event (data set subdivided in space). The feasibility of using this method on a daily basis is here investigated, i.e. radar estimates are adjusted using the experience gained from the previous day. This approach opens the door to the possibility of a future real-time use of the WMR method in the Alps. The analysis concerns four days of severe rainfall during the disastrous October 2000 Piedmont flood.

## 2. IMPROVING RADAR-DERIVED PRECIPITATION ESTIMATES

It is not surprising that raw radar estimates above collocated rain gages in a complex propagation environment, show a considerable underestimation: this is mainly caused by partial beam occultation and shielding by orography in combination with a decreasing vertical profile of radar reflectivity. The WMR method, like other radar-gage adjustment techniques, is based on the analysis of the Radar-to-Gage (R/G) ratio, often called the "Assessment Factor" (AF). This implies that a multiplicative model (rather than an additive one) has been chosen for the modeling and estimation of the errors in the radar estimates. This choice is often present in radar-rainfall literature: the fact that there is a dominance of multiplicative models in literature can be explained by the presence of multiplicative terms in the radar equation and, perhaps, also by speculating that multiplicative error models would lead to independence of the variance from the rainfall magnitude. In our conceptual model, the AF is seen as a measure of the "multiplicative error" that affects radar measurements taken at a certain altitude from the corresponding precipitation values at the ground. To reduce temporal fluctuations of the AF, it is helpful to integrate the precipitation in time (at a 60 km range, the radar samples a $\approx 10^8$ $m^3$ volume aloft once every 5 minutes; the rain gage continuously records –order of magnitude of the "integrated volume" in five minutes: $\approx 30$ $m^3$– at a single point on the ground). In the Alpine environment considered in this study, a daily integration period was chosen so as to try minimize the uncertainty caused by mismatches in time and space of the two types of instruments as well as that caused by changes in storm microphysics. In its present form, the WMR method therefore uses the daily AF as the response variable and tries to "explain" its variability in space in terms of the following three independent variables: (1) D, the Distance between the radar and the gauges (this being significant as it reflects the altitude of the beam as well as beam broadening and, to some extent, attenuation); (2) HV, the Height a meteorological target must reach over the gauge-pixel to be Visible to the radar; (3) HG, the Height of the Gauge (corresponding to the altitude of the terrain; this reflects the depth of the layer where precipitation growth related to orography can occur). These effects, together with the vertical profile of reflectivity, lead to biases: usually a relevant underestimation of rainfall by radar at longer ranges and at larger HV, and a small under- or over-estimation associated to HG, depending on whether growth or evaporation is dominant. Note that the vertical profile of reflectivity also includes the influence of the bright band and of the water- and ice-phases. As the precipitation process and the bright band are linked to the absolute height above sea level, better results have been found using HV and HG separately, rather than as the difference between the two. In Sec. 4 of [3], the basic ideas behind the WMR are described in detail, as well as the explanation of why the residuals of the non-linear multiple regression have to be weighed according to the geophysical quantity of interest to obtain the best results (in hydrological applications these geophysical quantities are obviously precipitation amounts).

Once the regression coefficients have been determined, the complete map of correction factors can be calculated, provided a map of the lowest visible echo have been already computed (i.e. a map of HV) for the given radar site, orography and refractivity, A computer code for radar site assessment has been used [5] for this purpose. In its simplest version, the code needs only a raster Digital Elevation Model, the radar parameters and an estimate of the mean atmospheric refraction. A word of caution concerning the correction procedure should here be made: since an equivalent

Earth's radius approach is used to compute the map of HV, the more similar the atmospheric refractivity gradient is to the one used by the code, the more effective is the correction based on the WMR method.

## 3. CASE STUDY

The area of interest is a hilly and high mountain region of approximately 12000 km$^2$ (northern part of Piedmont). The ground instrumentation includes a network of telemetered rain gages and a Doppler radar. The analysis concerns the 13-16 October 2000 Piedmont flood (a description of the event can be found in [6]): the data include measurements from 71 rain gauges and 5-minute full volume three-dimensional (3D) reflectivity maps acquired by the C-band radar. An estimate of the precipitation rate that reaches the ground is recorded in the so-called "RAIN" product. All clutter-free reflectivity measurements along the vertical are converted into the equivalent rain rate using a single Z-R relationship (($Z= 10^{2.5} R^{1.5}$) and then weighted with weights that are inversely proportional to the reflectivity heights in order to extrapolate the rain rate on the ground. In this paper, this "RAIN" product was used to derive the collocated radar amounts above the gauges (raw data). The daily raw radar estimates were then corrected using the experience gained from the previous day: the data from October 13, 14 and 15 were used to derive the correction coefficients to be applied to the following days. In the case of the WMR method, four correction coefficients were derived (in addition to an overall bias, radar estimates were corrected as a function of distance, height of the weather echo and height of the terrain, Sec. 2), while in case of the bulk-adjustment, the overall correction factor was simply the "previous-day" Gage-to-Radar total.

## 4. RESULTS

The areal estimate of precipitation is of major interest for hydrology. The agreement between radar-derived and gage-derived rainfall estimates was checked at points where information from *in situ* measurements were available. In addition to the usual mean (areal) difference between Radar- and the Gage-*d*aily amounts, $E\{\mathbf{R}_d–\mathbf{G}_d\}$, the spread of the differences around the mean at each site is presented. As far as the description of the spread of these "errors" (i.e. "point" Radar-Gage differences) is concerned, we opted for the standard deviation, even though the distributions are usually skewed and not normally distributed for non-adjusted radar data. To ease comparison with other studies and between different days, the mean bias and the standard deviation of the error, $std(\mathbf{R}_d–\mathbf{G}_d)$, were normalized to the mean precipitation measured by the gages. The results are shown in Table 1: even a simple 1-parameter, bulk adjustment is able to reduce the mean bias in the region, but only a 4-parameter, non-linear Weighted Multiple Regression is able to significantly reduce the spread of the differences between remotely sensed and *in situ* measurements at each ground control point.

## 5. CONCLUSIONS

This study confirms the "during-the-fact" effectiveness of Weighted Multiple Regression (WMR) method to correct radar precipitation estimates in complex-orography regions. The feasibility of using the experience gained during a previous event to adjust another event was verified within the European COST 717 program [7].

Table 1. Improvement in the Radar estimates of precipitation above 71 Gages after applying a simple bulk-adjustment or the WMR-adjustment technique: overall daily Radar-to-Gage ratio (column 3) and normalized spread of the differences between Radar and Gage at each station (column 4). The correction coefficient(s) are tuned using 71 Radar/Gage daily amounts measured during the previous day of the October 2000 flood.

| Type of data | $E\{\mathbf{G}_d\}$ | $\dfrac{E\{\mathbf{R}_d\}}{E\{\mathbf{G}_d\}}$ | $\dfrac{std(\mathbf{R}_d - \mathbf{G}_d)}{E\{\mathbf{G}_d\}}$ |
|---|---|---|---|
| October 14, Raw data | | 0.19 | 0.67 |
| October 14, Bulk-adjusted data | 73.8 mm | 1.22 | 0.53 |
| October 14, WMR-adjusted data | | 1.16 | 0.49 |
| October 15, Raw data | | 0.15 | 0.44 |
| October 15, Bulk-adjusted data | 118.2 mm | 0.79 | 0.44 |
| October 15, WMR-adjusted data | | 0.70 | 0.36 |
| October 16, Raw data | | 0.11 | 0.68 |
| October 16, Bulk-adjusted data | 36.8 mm | 0.73 | 0.71 |
| October 16, WMR-adjusted data | | 0.61 | 0.63 |

On that occasion however, both the training and verification were based on precipitation amounts cumulated over the whole event (hence giving a more robust estimate of the Radar-to-Gauge ratio on which the WMR correction is based). In this study the feasibility of using the WMR method on a daily basis is investigated for the first time, i.e. radar estimates are adjusted using the experience gained from the previous day. The success of the results would seem to open the door to the possibility of using the WMR method for real-time correction.

## 6. REFERENCES


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