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Radar Measurement of Precipitation in non-optimal Conditions

by

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Abstract

Differences between the radar-estimated rainfall aloft and the corresponding raingauge-measured rainfall at the ground can be corrected by various techniques. In this article, three typical representatives of the following three main correction classes are statistically evaluated and inter-compared, using a common radar/raingauge data set: assessment factors, regression functions, and vertical extrapolations. Each correction method diminishes radar errors to a significant extent. Mean regional hourly overestimations up to 2 dB in the melting layer and mean underestimations up to -5 dB above it are all corrected to about 0 dB. The most promising method for operational applications turns out to be the vertical extrapolation of precipitation fields. The method is physically sound, simple to implement, and well suited for operational applications in real time.

1. Introduction

It is well known that the accuracy of radar estimates of precipitation at the ground depends crucially on the radar beam diameter and height relative to the precipitation melting layer.

By limiting radar measurements bellow the melting layer, close to the ground and close to the radar, where the beam diameter is small, typical discrepancies up to several tens of percents between the gauge-measured rainfall at the ground and radar-estimated rainfall in the beam are observed, depending on the rainfall integration time and area (Harrold et al., 1974). The main cause for errors in these *optimal* measuring conditions is the variability of the drop size spectrum and, consequently, the variability of the reflectivity–rainfall rate relation.

When radar measurements occur in the precipitation melting layer or above it, high over the ground and/or far from the radar, where the beam diameter is large, substantial deviations of the radar-estimated rainfall aloft from the ground truth are observed. Overestimations are found in the melting layer and underestimations above it; both can reach a factor of 5 or more (Joss and Galli, 1981). The main cause for errors in these *non-optimal* measuring conditions is the vertical inhomogeneity of precipitation fields combined with the inability of the radar to measure close to the ground due to the orography and/or earth curvature.

To improve the accuracy of radar estimates of precipitation at the ground in non-optimal measuring conditions, various methods can be applied. These "correction" methods can be grouped into three main classes: direct calibrations with raingauges, indirect calibrations with raingauges, and vertical extrapolations of precipitation fields. Direct calibrations make use of experimentally determined radar-to-gauge rainfall ratios (Wilson, 1970; Collier et al., 1983). Indirect calibrations rely on various experimentally tuned regression functions, both linear (Joss and Galli, 1981) and non-linear (Cappellini et al., 1994). Vertical extrapolations utilize vertical profiles of rainfall rate (Joss and Lee, 1995) or reflectivity in various degrees of complexity (Koistinen, 1992; Andrieu and Creutin, 1995; Kitchen et al., 1994).

The aim of this study is to formulate, calibrate, and evaluate three typical representatives of the three main correction classes described above, using a common radar/raingauge data set. In this way it is hoped to contribute to answering the question which method is best suited for operational applications in real time, specifically for point measurements of hourly rainfall accumulations.

2. Formulation of representative techniques

a. *Regional seasonal assessment factors*

The simplest method for correction of radar errors is the use of assessment factors. At each ground location with the installed raingauge, the ratio between radar and gauge measurements of rainfall is calculated by using yearly, seasonal, monthly, daily or even hourly accumulations. These radar-to-gauge ratios are assumed to be representative in neighbourhoods of the gauges, and new radar data are multiplied with their reciprocal values – the so-called assessment factors. Usually logarithmic values of assessment factors and rainfall amounts are used, thus preserving the symmetry between radar and raingauge measurements and replacing multiplications with additions. The connection between the rainfall at the ground G and the radar-estimated rainfall aloft R has the form

$$10 \log G = 10 \log R + 10 \log A(\mathbf{x}, t), \tag{1}$$

with $A(\mathbf{x}, t)$ denoting location and time dependent assessment factors. There are as many ways how to determine and use assessment factors as there are authors (Wilson, 1970; Brandes, 1975; Collier et al., 1983). This paper concentrates on regional seasonal factors from the following reasons.

The main cause for radar errors in non-optimal measuring conditions is the vertical inhomogeneity of precipitation fields which is closely related to the height of the 0° isotherm. This height changes with time. In middle geographical latitudes, summer-to-winter changes of the isotherm height amount up to 3–5 km which is several times more than the average radar beam diameter in the radar coverage area. The yearly assessment factor does not, therefore, communicate all the available information because it contains both over- and underestimations which partially cancel out. On the other hand, seasonal variations in the height of the 0° isotherm are comparable with the radar beam diameter, and seasonal assessment factors seem to be much better candidates. Shorter time periods are again less suitable because changes in the height of the 0° isotherm become small relatively to the beam diameter at medium and long ranges. Consequently, daily and hourly assessment factors seem to be adequate mainly for measurements in optimal conditions. Even then, one has to be careful in their application in order not to make things worse (Koistinen and Puhakka, 1984).

Similar arguments as in the case of the temporal averaging are valid for the spatial averaging. A single assessment factor for the whole radar coverage area has obviously not much sense. On the other hand, special assessment factors at every gauge location can contain errors which are not representative for their neighbourhoods. The best candidates seem therefore to be regional assessment factors, i.e., factors calculated from groups of raingauges located in approximately homogeneous geographic sub-areas with the horizontal size of the order of 20 km.

b. Regression of rainfall on measuring conditions

The field of assessment factors $A(\mathbf{x},t)$ can be approximated analytically with a suitable function of time and location or related variables such as distance from the radar, beam height, orographic height etc. Again, both the form of the function and the choice of variables vary from author to author (Joss and Galli, 1981; Cappellini et al., 1994). This paper concentrates on the simplest form of the function, the linear dependence. The following two independent variables are furthermore selected: absolute displacement $|\Delta h|$ of the beam axis from the estimated melting layer height, and beam diameter D. The reasons are as follows.

The observed dependence of assessment factors on location and time is not "real"; it just reflects the influence of other – more or less known – physical variables on the measuring process. Time dependence indicates the influence of the melting layer position relative to the (fixed elevation) radar beam. In a relatively flat orography, location dependence is reduced to a systematic range dependence which can itself be replaced with the dependence on the beam height and diameter if absorption along the beam is neglected. However, beam height over the ground is – partially at least – already taken into account by the beam height relative to the melting layer, so it can be discarded. Thus only variables D and Δh remain, with local symmetry of the vertical reflectivity profile at the melting layer suggesting the use of $|\Delta h|$ instead of Δh.

Rainfall at the ground, radar-estimated rainfall aloft, and two variables describing measurement conditions are inter-connected via the equation

$$10\log G = a + b\,10\log R + c\,D + d\,|\Delta h| \tag{2}$$

with unknown coefficients a, b, c, and d. Their numerical values must be determined experimentally, from radar/gauge measurements, with the requirement to minimize the root-mean-square difference between the left and right side of the equation. The regression equation with calibrated coefficients can then serve for correcting new radar data.

c. *Vertical extrapolation with synthetic profiles of reflectivity*

Regression functions enable the prediction of the true rainfall at the ground from the radar-estimated rainfall aloft and serve, in a sense, as a tool for vertical extrapolation of precipitation fields. However, they do not take into account vertical field profiles explicitely. This can be accomplished by specific vertical extrapolation techniques. The arguably best technique of this kind is based on the beam-weighted vertical integral of reflectivity Z:

$$\bar{Z}/Z_g = \int z(h + r\beta)\bar{f}^2(\beta)d\beta, \tag{3}$$

where $\bar{Z}$ denotes reflectivity at the slant range r and height h (estimated by radar using the standard radar equation), Z_g reflectivity at the ground, and z the ground-normalized reflectivity profile inbetween. Horizontally integrated two-way beam pattern is denoted by $\bar{f}^2$, and the vertical integration angle relative to the beam axis by β. If the vertical profile is known, reflectivity at the ground can be calculated and subsequently transformed into rainfall via the reflectivity–rainfall rate relation.

The key to the successful application of the method lies in the estimation of the true profile over each ground location. Different authors adopted different solutions, using either actually measured average profiles (Koistinen, 1992; Andrieu and Creutin, 1995) or parameterized synthetic profiles (Kitchen, 1994). This paper investigates the use of local hourly synthetic profiles relative to the (sounding-estimated) height of the 0° isotherm. Two types of profiles are postulated, one for convective and one for stratiform precipitation. The convective profile does not change with height. The stratiform profile is characterized by constant reflectivity bellow the melting layer, by triangularly-shaped melting layer of the depth D_0 and relative peak reflectivity Δz, and by constant logarithmic reflectivity gradient dz/dh above the melting layer. Local precipitation type is determined every hour at every ground location from the local rainfall aloft: when this rainfall exceeds the threshold R_0, convective precipitation is indicated. Stratiform profile parameters, together with the rain type threshold, can be specified using published profile observations (Fabry and Zawadzky, 1995) or experimentally, from radar/gauge measurements, with the requirement to minimize the root-mean-square difference between the ground truth and the vertically extrapolated rainfall to the ground. The extrapolation equation with calibrated profiles can then serve for correcting new radar data.

The preference for synthetic profiles over actual ones can be justified by their non-problematic availability and greater potential for solving problems with embedded convection and orographic growth.

3. Calibration and evaluation of techniques

For the calibration and evaluation of formulated rainfall estimation techniques, simultaneusly measured raingauge and radar data are needed. Archived data at CSIM (Experimental Center for Hydrology and Meteorology) in Teolo near Padua, Italy, were chosen for that purpose. CSIM is operating a C-band one-degree beam dual-polarisation Doppler radar and a dense network of ground raingauges in the Veneto region. Radar and raingauge measurements are performed every 15 minutes and archived for subsequent use. Archived data from the year 1992 were inspected and a subset of about 50 hours of radar measurements of reflectivity at the 1.5° elevation angle over each of the 80 selected raingauges was extracted, amounting up to about 5000 gauge-hours. Measurements in all seasons except winter were selected, including stratiform, convective, and mixed precipitation events in approximately climatological proportions. Radar measurements were transformed into hourly rainfall accumulations via the standard reflectivity–rainfall rate relation, and all subsequent analysis was performed on radar/raingauge pairs of hourly rainfall. Heights of the 0° isotherm were extracted from 12 GMT soundings at the nearby radiosonde station in Udine.

The complete set of radar/raingauge data pairs was randomly split into two subsets, one for the calibration and one for the evaluation process. Calibration of investigated correction techniques, described in the previous section, reveals regional seasonal assessment factors for the Veneto region (and the 1.5° elevation scanning), regression coefficients for the regression equation (2), and profile parameters for the vertical extrapolation equation (3). It must be noticed, however, that although calibration and evaluation were performed on two disjoint data sets, the same set of raingauges was used, by necessity, for both processes.

Calculated assessment factors are specific to the selected geographical subregions and are not presented here. Regression parameters turn out to be $a = -0.37$, $b = 0.61$, $c = 0.24/\mathrm{km}$, and $d = 0.11/\mathrm{km}$, whereas profile parameters obtain the following (sensible) values: $D_0 = 1.0$ km, $z_0 = 7.5$ dB, $dz/dh = -5$ dB/km, and $R_0 = 10$ mm. The depth of the melting layer D_0 is slightly overestimated, indicating a numerical compensation for occassional inacurracies in estimates of the 0° isotherm height. Among all profile parameters, the last one is least significant, showing a relatively small statistical importance of convection in comparison with stratiform precipitation.

With correction techniques calibrated, the experimental evaluation of techniques can be performed straightforwardly using the evaluation data set. The results are displayed in Figs. 1 and 2. Figs. 1a-c show frequency distributions of radar errors in the evaluation data set for non-corrected and corrected radar data. Dispersions of local hourly radar errors σ_A around their mean values $\bar{A}$ are significantly reduced by all three correction techniques: from 4.4 dB to 3.4–3.6 dB. This indicates the reduction of average local radar errors from a factor of 2.8 to a factor of about 2.2.

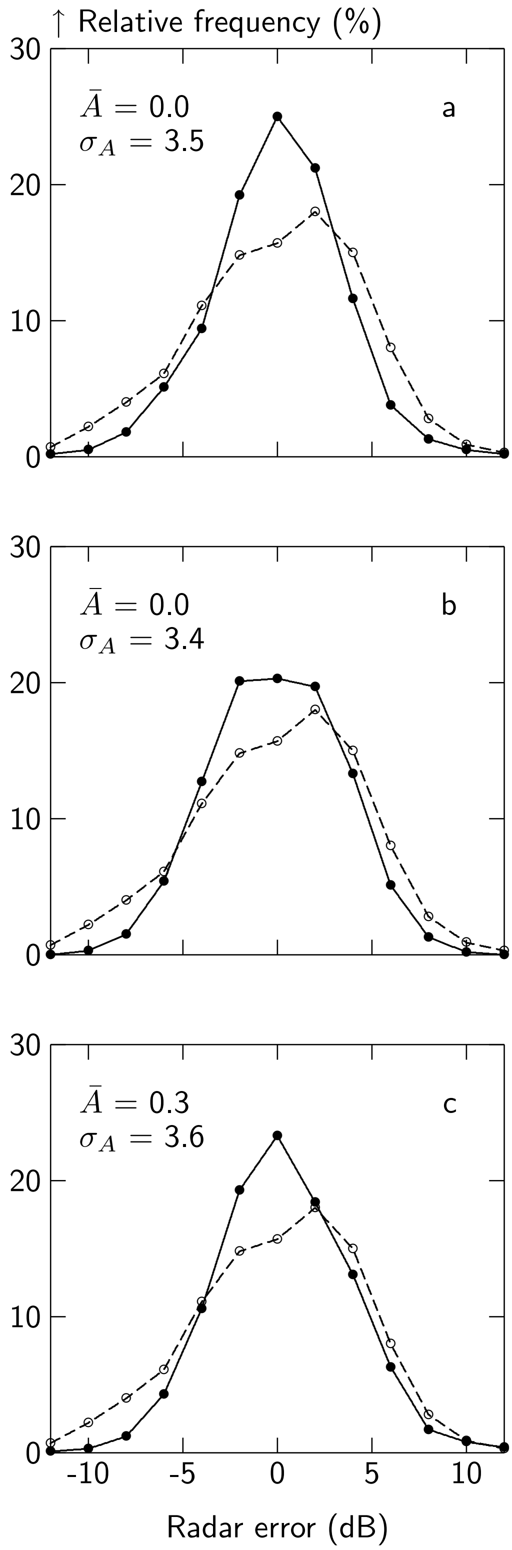

Fig. 1a-c. Distribution of radar errors. Corrections by assessment factors (a), linear regression (b), and vertical extrapolation (c).

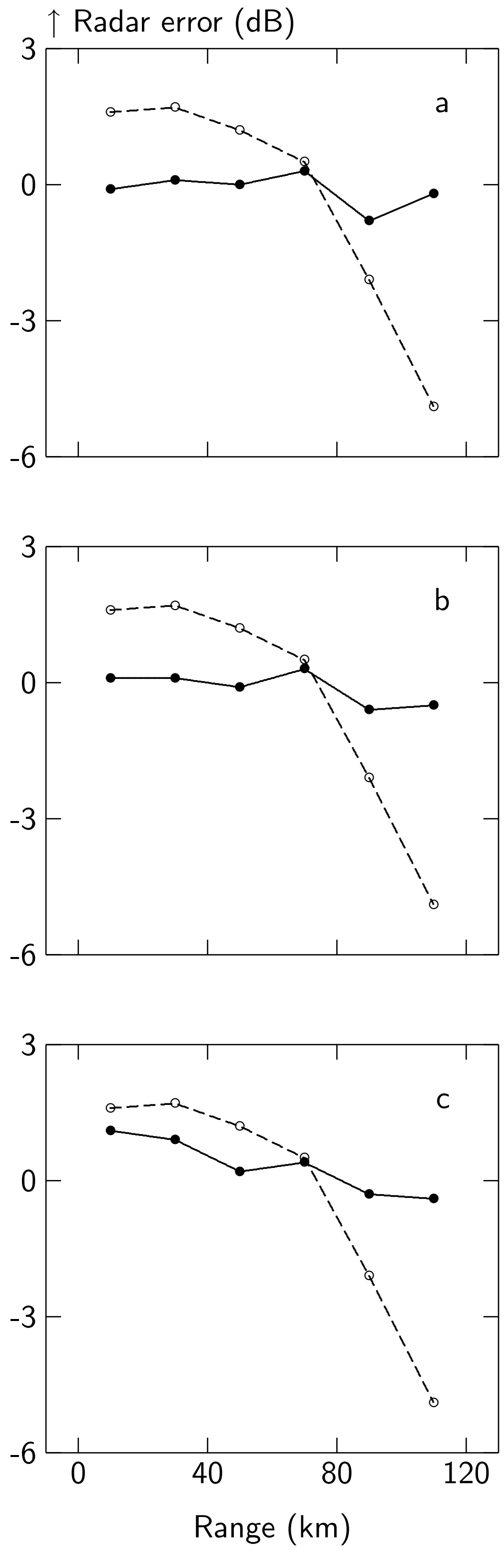

Fig. 2a-c. Range dependence of radar errors. Corrections by assessment factors (a), linear regression (b), and vertical extrapolation (c).

It is interesting to notice that the reduction of local radar errors does not influence the mean radar error over the whole radar coverage significantly. This error is negligible (0.1 dB) already in non-corrected radar data due to the combined effect of the selected radar range, beam elevation, raingauge distribution, and typical heights of the 0° isotherm during the observation period: systematic underestimations at long ranges just cancel out systematic overestimations at medium ranges.

The effect of correction procedures can be seen even better in Figs. 2a-c which show the range dependence of average radar errors in concentric regions around the radar site. Systematic overestimations at medium ranges and underestimations at long ranges are significantly diminished by all three correction techniques. Overestimations up to 2 dB at medium ranges and underestimations up to -5 dB at long ranges are reduced to about 0 dB. Some problems with the elimination of overestimations at close ranges by the vertical extrapolation technique can be observed. This is a consequence of errors in the estimation of the (variable) melting layer height which was assumed to be constant during each day.

The efficiency of correction methods can be conveniently quantified via correlation coefficients between raingauge and radar data. They are presented in Tab. 1.

Table 1. Efficiency of correction techniques in non-optimal measuring conditions. Correlation coefficients between radar and raingauge local hourly accumulations are denoted by r, and dispersions of local radar errors by σ_A.

Method	σ_A (dB)	r
No correction	4.4	0.49
Assessment factors	3.5	0.65
Linear regression	3.4	0.60
Vertical extrapolation	3.6	0.62

The best skill in estimating ground rainfall is exhibited by assessment factors: the correlation coefficient between the predicted and actual ground rainfall is 0.65. This means a significant improvement when compared with the correlation coefficient of 0.49 between the non-corrected radar data and the ground truth. Good performance of regional seasonal assessment factors – in terms of the prediction skill – is not surprising if it is recalled that these factors take into account both main causes for radar errors (beam diameter and height relative to the melting layer) together with less important ones (orography, attenuation etc.). However, assessment factors have two serious drawbacks for operational implementations: first, a dense network of raingauges is needed for calibration, and secondly, the field of assessment factors is strongly dependent on the local radar beam width, scanning elevation angle, climatology, and orography. Any change in measuring conditions, for example a change of the scanning angle, makes previously established assessment factors useless.

The second-best skill is exhibited by the vertical extrapolation technique, producing the correlation coefficient of 0.62. This is not much less than obtained with assessment factors, and the slightly worse performance can be attributed to the crude parameterization of vertical profiles. Moreover, vertical extrapolation at close ranges is quite sensitive to the accurate estimation of the 0° isotherm height, which was assumed to be constant during each day. It is obvious that the parameterization of vertical profiles and determination of the melting layer height can be improved significantly (Kitchen, 1994), thus suggesting the further possible increase in the prediction skill. Nevertheless, the main strength of the method lies in its flexibility, transferability, and ease of implementation. No raingauges are usually needed for calibration, and the method can easily take into account different beam widths, scanning angles and climatology of the 0° isotherm height. With some efforts, orographic effects could be accounted for as well.

The least skilled method is the linear regression of rainfall on measurement conditions, which exhibits the correlation coefficient of 0.60. However, the improvement over the non-corrected data is still significant. The lower skill of the method, compared with assessment factors, could be explained by the assumed linearity of the regression (which is only a first-order approximation), and by the neglection of orographic effects. The method needs raingauges for calibration, but once calibrated, it is applicable to different radar installations, and to some extent even to not-so-different climatologies. This is a consequence of suitably chosen regression variables.

4. Conclusions

In the study, the following three radar data correction techniques devised for non-optimal measuring conditions were formulated, calibrated, and evaluated: regional seasonal assessment factors, linear regression of rainfall on the beam diameter and displacement from the melting layer, and vertical extrapolation of precipitation fields with parameterized profiles of reflectivity. Calibration and evaluation were performed on a set of about 5000 radar/raingauge pairs of point hourly rainfall, simultaneusly measured by a C-band radar at 1.5° elevation angle and by 80 raingauges located around the radar up to the range of 120 km. All seasons except winter were represented and all precipitation types – stratiform, convective, and mixed – were included in approximately climatological proportions. The following was found.

Every correction technique diminishes radar errors to a significant extent. Interestingly, all techniques display approximately the same skill in reconstructing the true surface rainfall from the radar estimated rainfall aloft. Mean regional overestimations up to 2 dB at medium ranges and underestimations up to −5 dB at long ranges are reduced to about 0 dB. Average local radar errors are diminished from 4.4 dB to 3.4–3.6 dB, and the correlation coefficient between radar and raingauge data increases from 0.49 to 0.60–0.65, depending on the technique.

Judging by correlation coefficients alone, the most appropriate method for operational applications in real time might seem to be the use of assessment factors. However, this method has a serious drawback: it requires a dense network of raingauges for calibration. On the other hand, the vertical extrapolation of precipitation fields usually does not need any raingauges for calibration, and its performance (in this study) is only slightly worse than the performance of assessment factors. Moreover, the method is physically well-grounded, easily adaptable to changes in radar characteristics or scan strategies, and quite capable of further improvements. All this seems to make it – among the three methods tested in this study – the best choice for radar measurements of precipitation in non-optimal conditions.

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