Improved radar data processing algorithms for quantitative rainfall estimation in real time

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ABSTRACT

This paper describes a new methodology to process C-band radar data for direct use as rainfall input to hydrologic and hydrodynamic models and in real time control of urban drainage systems. In contrast to the adjustment of radar data with the help of rain gauges, the new approach accounts for the microphysical properties of current rainfall. In a first step radar data are corrected for attenuation. This phenomenon has been identified as the main cause for the general underestimation of radar rainfall. Systematic variation of the attenuation coefficients within predefined bounds allows robust reflectivity profiling. Secondly, event specific $R$–$Z$ relations are applied to the corrected radar reflectivity data in order to generate quantitative reliable radar rainfall estimates. The results of the methodology are validated by a network of 37 rain gauges located in the Emscher and Lippe river basins. Finally, the relevance of the correction methodology for radar rainfall forecasts is demonstrated. It has become clearly obvious, that the new methodology significantly improves the radar rainfall estimation and rainfall forecasts. The algorithms are applicable in real time.

Key words | attenuation, forecast, microwave link, radar rainfall, $R$–$Z$ relation

INTRODUCTION

Weather radars offer an unprecedented opportunity to observe rain storms and to quantify rainfall intensity in space and time. In combination with storm tracking and extrapolation methods they therefore have a tremendous potential for real time control (RTC) of drainage systems (Krämer & Verworn 2005; Krämer et al. 2007; Verworn & Krämer 2008). The quantitative use of radar data in these applications, especially as direct input into hydrodynamic models to predict runoff and flows in order to define control decisions, is strongly limited by the basic measurement of reflectivity $Z$ and its conversion into rainfall intensity $R$. Rainfall intensities derived from C-band radars show a notable underestimation which is due to the effect of signal attenuation by the intervening rainfall itself (Battan 1973; Delrieu et al. 1999; Collier 2007). The adjustment of radar data with the help of rain gauges to compensate this phenomenon in real time is problematic for several reasons. First, correction factors obtained by radar gauge comparisons do not account for the physical raincell structure and the high non-linearity which is incorporated in the rainfall process. Second, rainfall has to be measured by the gauges first, before data are processed and compared with radar data. Further, to obtain robust results, it is advisable to integrate radar and gauge observations over a certain time span (Zawadzki 1975, Krajewski & Smith 2002). Transmission, processing and integration of data may result in a time-lag which reduces the up-to-dateness of the adjusted radar data, which is critical in urbanized areas with their dynamic rainfall runoff responses. The preferring alternative is a deterministic, physically orientated approach for the data processing, which accounts first in detail for the specific radar signal attenuation $k$ [dB km$^{-1}$] due to the rainfall itself ($k$ – $Z$ relation), and second for type specific conversion of reflectivity $Z$ [mm$^6$ m$^{-3}$] into rainfall.

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intensity $R$ [mm hr$^{-1}$] ($R$–$Z$ relation). This paper presents a new data processing methodology which incorporates both aspects.

A dual frequency microwave link extending over a distance of 26.9 km was installed almost parallel to a single radar ray to measure the amount of attenuation the radar signal might have experienced. An extended analysis of the variability of attenuation coefficients for radar signal correction was performed. The results provide an a priori knowledge for the radar attenuation correction in real time. The important feature is that no further reference is needed. After attenuation correction of the radar reflectivity $Z$-matrices the estimation of the $R$–$Z$ relation (stratiform/convective type) becomes relevant to process radar data for the target figure rainfall intensity $R$. For quantitative validation the processed radar data are compared with ground rainfall observed by 37 rain gauges. In RTC the knowledge of future rainfall over a horizon of several hours ahead improves the effectiveness of control decisions. Hence, the relevance of the radar data processing methodology for RTC is demonstrated by comparing rainfall forecast generated by the radar rainfall forecast model HYRATRAC (HYdrological RAdar TRACing) for uncorrected and corrected C-band radar rainfall.

**RAINFALL OBSERVING NETWORK, DATA AND CATCHMENT**

The rainfall observing network is located north of the City of Essen, Western Germany in the Emscher and Lippe river basins (Figure 1). It consists of a C-band radar, a dual frequency microwave link, a disdrometer and 37 tipping bucket rain gauges.

**C-band radar data**

The C-band radar with a frequency of 5.6 GHz is operated by the German Weather Service. The analysis focuses on the precipitation scan, which measures rainfall closest to the ground with an elevation of $\alpha = 0.5^\circ$. The data are provided with a time resolution of $\Delta t = 5$ minutes between successive data sets. For attenuation correction analysis radar data in polar coordinates (DX-product) have been used. A data set consists of 360 radar rays (azimuthal resolution = 1°), and each radar ray is subdivided into 128 gates with a gate length of $\Delta r = 1$ km. The measured radar reflectivity is discretised into 128 dBZ classes.

For the rainfall forecasting with HYRATRAC the polar radar data (DX-product) have been processed into a Cartesian grid format (PF-product) with a pixel size of $1 \times 1$ km. The radar reflectivity values were aggregated into 16 dBZ classes.

**Dual frequency microwave link**

The microwave link consists of a transmitter which continuously transmits pulsed power to a remote receiver. Two transmitters operating at different frequencies 10.5 GHz and 17.5 GHz have been installed on a telecommunication tower near the City of Recklinghausen in 70 metres height. The two receivers were mounted on an X-band radar tower in a distance of 200 metres from the C-band radar location. Thus, for an instant moment or rather angle ($= 35^\circ$ → ray no. 35), the rotating C-band antenna transmits and receives the backscattered signal almost parallel to the link propagation path. Therefore, the link provides a reference for the rain induced attenuation the radar signal might have experienced along the 29.6 km link path (Figure 1).
Disdrometer

The disdrometer (JW-D) measures the size and number of raindrops (DSD) for a defined time interval of $\Delta t = 1 \text{ min}$ and a sampling area of $50 \text{ cm}^2$ (Joss & Waldvogel 1967). It distinguishes the drop diameters into 20 drop size classes ($D_i$) with a minimum drop size class of $D_{\text{min}} = 0.34 \text{ mm}$ and a maximum size of $D_{\text{max}} = 5.2 \text{ mm}$. Even though the direct comparison of DSD aloft and at the ground may be affected by many uncertainties described by Austin (1987) it is assumed that the measurement at the ground provides a reasonable estimate of the DSD as seen by the radar aloft, which determines the scattering processes of the radar signal. DSD measurements are used to derive empirical relations between specific attenuation $k$ and reflectivity $Z$ ($k-Z$ relation) as well as for the scaling of reflectivity $Z$ into the rainfall intensity $R$ ($R-Z$ relation).

Catchment

The catchment Hüllerbach (Figure 1) is a highly urbanised area with a total size of $5,130 \text{ ha}$. One hundred radar pixels (PF-product) cover the target area and contribute to the areal rainfall. Rainfall forecasts made with the HYRATRAC model are being analysed for this area.

RADAR DATA PROCESSING METHODOLOGY

The attenuation phenomenon and correction principle

The phenomenon of radar signal attenuation with range due to the microphysical properties of the intervening rainfall is illustrated in Figure 2. The signal attenuation at X- and C-band frequencies on a single raindrop depends on its shape, its size $D$ and the temperature. The drop shape and size define the scattering cross sections ($\sigma_s$, $\sigma_s$, $\sigma_a$) which balance the transmitted and incident power ($P_t$). While some power is scattered ($P_t \times \sigma_s$) and absorbed ($P_t \times \sigma_a$) only a very small proportion is backscattered to the radar antenna ($P_r$). The scattering and absorption processes reduce the power of the transmitted signal and are subsumed as attenuation [dB] or specific attenuation $k$ [dB km$^{-1}$]. The backscattered signal is related to radar reflectivity $Z$ [mm$^6$ m$^{-3}$]. For rainfall as seen by the radar the scattering processes on a single raindrop are integrated over all raindrops in the scanning volume. The number of drops $N$ and their distribution with size $N(D) \text{ dD}$, however, is unknown. Due to this and since no direct physical relation exists between the attenuation and backscattering, the relation between the two quantities $k$ and $Z$ is expressed by a power law of the form $k = a \times Z^b$, where $a$ and $b$ are the attenuation coefficients which quantify the radar signal scattering.

![Figure 2](https://iwaponline.com/wst/article-pdf/60/1/175/448723/175.pdf)
Hitschfeld & Bordan (1954) and Marzoug & Amayenc (1994) proposed an algorithm for the correction of the signal attenuation with range to the original transmitted power level, depending on the rainfall characteristics along the radar ray. The correction principle is illustrated in Figure 3.

Owing to the radar data processing the correction algorithm has to be implemented in a gate by gate approach. Starting from the origin of a radar ray at the radar site the attenuation for the first gate is calculated from the reflectivity value of that gate using $k = a \times Z^b$. The reflectivity of all gates beyond is then increased by this proportion. Consequently, for a given gate $i$ of a radar ray the attenuation $k_i$ is calculated from the measured reflectivity value ($Z_i$) plus the sum of attenuation from the preceding gates ($\sum k_j$). This procedure is described in the following formula in which $D_r = 1.0$ km is the length of the radar gates and the factor of two is to consider the two way attenuation the radar signal experiences.

$$k_i = a \times \left( Z_i + \sum_{j=0}^{i-1} k_j \times 2D_r \right)^b$$

This algorithm is inherently unstable and may diverge from the sensible range of reflectivity if the attenuation is overestimated. This may be due to radar calibration issues, clutter echoes and inexact assumptions of the attenuation coefficients $a$ and $b$. Normally, the attenuation coefficients ($a$, $b$) are defined by scattering simulations based on point measurements of DSD at the ground. Even though there is little evidence that point approximations of DSD are adequate in view of the existing spatial and temporal variability of the rainfall process these coefficients are constantly applied in correction algorithms (Harrison et al. 2000). Delrieu et al. (2000) state that with the use of constant coefficients stable corrections can only be expected in the range of up to 10 dB. Since corrections higher than 10 dB may be required locally, the danger of overcorrection and instability is always inherently present and prevents operational application of these approaches.

### Attenuation reference

The radar attenuation ($A_{\text{Radar}}$) to be compared with the reference attenuation along the 29.6 km link path in the following analysis is

$$A_{\text{Radar}} = \sum_{i=0}^{29} k_i$$

In contrast to the radar, where there is a factor at the magnitude of $10^{-17}$ between the transmitted and received signal power level, the amplitude of the microwave link is directly measured (Figure 2). Therefore, a robust receiving signal is provided. For utilization as a reference for correction analysis the amount of the total path integrated attenuation due to rainfall has to be determined and compared to the receiving signal level during dry conditions straight before and after the event. This is known as the baseline problem. To account for it when processing rain induced attenuation time series, an algorithm following Upton et al. (2005) has been applied. This algorithm uses the correlation of the received power of the two frequencies and the five rain gauges closest to the link (black circles in Figure 1) as independent sensors for categorical information about the presence of rainfall.

A frequency scaling is necessary to compare the attenuation characteristics of the 10.5 GHz link frequency ($A_{10.5\text{GHz}}$) with those of the radar frequency at 5.6 GHz ($A_{5.6\text{GHz}}$). For conversion a quadratic function has been proposed by D’Amico (2004):

$$A_{\text{Reference}} = A_{5.6\text{GHz}} \times 0.0079 \times A_{10.5\text{GHz}}^2 + 0.1751 \times A_{10.5\text{GHz}} - 0.0012$$

An analysis of the link time series for the year 2003 suggested five rainfall events for which the link signal
experienced severe (one way) attenuation. The events showed a marked convective character as can be seen by the rainfall range observed by the five rain gauges closest to the link (Table 1). The rainfall derived from the attenuation difference of the two link frequencies is in good agreement with the gauge rainfall which is weighted with a Thiessen approach. Details for link derived rainfall are given in Upton et al. (2005) and Krämer (2008).

All events have been processed on a minute basis for the attenuation reference time series (AReference). The scaled maximum attenuation at 5.6 GHz exceeded 3.0 dB for each event. In terms of the logarithmic scaling a value of 3.0 dB denotes a bisection of the radar reflectivity.

For June 8 and July 16 path integrated attenuation of even more than 6.0 dB was observed. To compare the one-way link attenuation reference with the two-way radar attenuation, AReference has to be multiplied with a factor of two. Therefore, in case of June 8, the PIA of 2 × 6.3 = 12.6 dB indicates an underestimation of radar reflectivity and rainfall beyond a distance of 29.6 km with a factor of 2². This demonstrates the necessity to account for the radar signal attenuation for correction.

### Attenuation coefficient analysis

With the existence of an attenuation reference parallel to the C-band radar beam no. 35 the basis for an extended analysis of the attenuation correction algorithm and the appropriate coefficients is given. The idea was to compare the corrected radar attenuation (ARadar) depending on various coefficients (a, b) with AReference and to focus on those coefficients which give a minimum attenuation difference (ADif):

$$|A_{\text{Radar}}(a,b) - A_{\text{Reference}} × 2| ≤ A_{\text{Dif}}$$

An optimal combination of a and b was adopted when attenuation differences between ARadar and AReference were not larger than ADif ≤ ± 0.1 dB. The factor of two is to consider the two way attenuation the radar signal experiences. In contrast to an earlier study on the same experiment (Rahimi et al. 2006) the forward correction is preferred (Figure 3) since it is extremely sensitive to the choice of a and b. For comprehensive analysis the coefficients have been varied systematically in the range of 1 × 10⁻⁶ ≤ a ≤ 1 × 10⁻³ and 0.65 ≤ b ≤ 1.0. These bandwidths have been defined in accordance with findings from literature (Krämer 2008).

### Results of attenuation coefficient analysis

To illustrate the results the time series of AReference is plotted for June 8, 2003 in Figure 4 (left). A strong convective rain cell complex crossed the microwave link between 12:15 and 13:00 hrs UTC and induced significant path integrated attenuation between 1.5 dB to 12.0 dB. The minutes for which radar scans were sampled are indicated by the black dots.

In Figure 4 (right) the results of the coefficient analysis are given. The exponent b is plotted against the linear coefficient a. Thus, each dot represents a combination for which the difference between corrected radar attenuation and attenuation reference is less than 0.1 dB. Obviously, numerous a-b-combinations fulfill the objective criterion, which cover the entire bandwidth defined for a and b. For each minute many a-b-combinations are found which show an aligned character with a negative gradient (“minute-lines”). A good agreement with the coefficient combinations found in literature (black circles) is obvious. In contrast to the literature coefficients which have been derived from point measurements of DSD at the ground, the results of the “minute lines” may be interpreted as path integrated coefficients. These findings, the negative gradient of the “minute lines” and the high variability of coefficient combinations, were already mentioned by Park et al. (2005).

<table>
<thead>
<tr>
<th>Date</th>
<th>Rainfall (mm)</th>
<th>Microwave link (mm)</th>
<th>5.6 GHz (dB)</th>
<th>10.5 GHz (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 3</td>
<td>0.2</td>
<td>36.0</td>
<td>16.1</td>
<td>9.6</td>
</tr>
<tr>
<td>June 8</td>
<td>17.4</td>
<td>23.3</td>
<td>20.6</td>
<td>20.9</td>
</tr>
<tr>
<td>July 16</td>
<td>7.4</td>
<td>20.9</td>
<td>16.0</td>
<td>20.2</td>
</tr>
<tr>
<td>July 21</td>
<td>0.8</td>
<td>14.5</td>
<td>7.5</td>
<td>6.8</td>
</tr>
<tr>
<td>July 22</td>
<td>0.8</td>
<td>16.4</td>
<td>11.9</td>
<td>11.4</td>
</tr>
</tbody>
</table>
From these results it must be concluded that the use of a single combination of constant $a$-$b$-coefficients for attenuation correction of all radar rays and event minutes is not sensible and effective. The overall characteristic of optimal coefficients following “the minute lines with the negative gradients” is that a reduction of the exponent $b$ may be compensated by an increase of the linear coefficient $a$. The pure existence of these optimal coefficients and their characteristic allocation (“minute lines”) provide the basis for a real time estimation methodology of the coefficients even in absence of an attenuation reference (e.g. microwave link) for each individual radar ray.

For explanation of the coefficient estimation methodology the $a$-$b$-coefficients of a single minute are marked in Figure 4 (white dots). In addition, a lower and an upper bound are given. They denote the area of the parameter space in which minute lines of many events have been found. Under the condition that the exponent $b$ is fixed three different cases for estimation of the linear coefficient $a$ have to be distinguished. For $a > a_{\text{opt}}$ ($a_{\text{over}}$) the corrected radar attenuation ($A_{\text{Radar}}$) overestimates the attenuation reference ($A_{\text{Reference}}$). Divergence of the correction algorithm is likely, the higher $a$ is, and the more $a$ approaches the upper bound. Given the case that $a < a_{\text{opt}}$ ($a_{\text{under}}$), $A_{\text{Radar}}$ and the resulting reflectivity profile underestimate the truth, but the correction algorithm performs always stable. The third case $a = a_{\text{opt}}$ describes the ideal estimation of the linear coefficient $a$ in absence of $A_{\text{Reference}}$.

Real time attenuation correction methodology

Since an attenuation reference for operational purposes in real time does not exist for each radar ray and minute, an iterative procedure is proposed to estimate suitable combinations of $a$ and $b$. The idea is to adopt a combination of coefficients $a_0$, $b_0$ as an initial guess for the correction. It appears to be sensible to chose $a_0 = 2 \times 10^{-4}$, $b_0 = 0.70$ in order to rather overestimate the attenuation first. In case of instability which is typical for convective rainfall, the linear coefficient $a_0$ has to be reduced step by step for $\Delta a = 1 \times 10^{-5}$ until no divergence occurs, or $a_{\text{min}}$ ($= 3 \times 10^{-5}$) has been reached. The exponent $b$, however, should remain constant. Thus, the subsequent reduction of $a$ in case of divergence ensures that the unknown specific “minute-line” will be crossed (Figure 4). The closer the linear coefficient is to the specific “minute-line” the more likely is the stability of the correction. The choice of a low exponent $b$ is of advantage from a numerical point of view, since it was found that the density of optimal coefficient combinations is always higher for lower than for larger $b$. Following this methodology individual combinations of the attenuation coefficients are applied to each radar ray.

Even though the methodology provides an estimate for optimal and path averaged attenuation coefficients, their variable application proves to be a robust and is applicable in real time. This is a significant difference to the Hitschfeld & Bordan (1954) approach using a single combination of $a$ and $b$ leading to instability of the correction, especially in convective situations.
RESULTS

Radar reflectivity

The effectiveness of the proposed attenuation correction methodology is demonstrated by visualization of the radar reflectivity matrixes as plan position indicators (PPI) for June 8, 2003. Due to its marked spatial structure and the high reflectivity gradients the event can be classified as highly convective. In Figure 5 (left) the uncorrected reflectivity matrix \( Z_a \) of a single radar scan is given. The radius is 128 km. Several intense cell cores exist which show reflectivity values up to 50 dBZ. With the proposed attenuation correction methodology a powerful intensification of the intense cell cores to highest reflectivity is conspicuous (Figure 5, middle). Values \( Z_{\text{cor}} \) exceeding 54 dBZ are found.

In addition, the large magenta coloured precipitation fields in the north with medium reflectivity (25–30 dBZ) have been increased to 58 dBZ with a large spatial extent. The reflectivity difference \( A_{\text{Dif}} = Z_{\text{cor}} - Z_a \) demonstrates the effect of attenuation and the capability of the correction to account for spatial differentiation of the reflectivity (Figure 5, right). Corrections ranging between 0 dB up to 20 dB have been calculated. The physical structure of the rain fields is preserved and recovered reasonably well and proves that the use of radar gauge adjustment techniques is strongly limited in convective situations.

\( R-Z \) relation estimation

For conversion of corrected reflectivity \( Z \) into rainfall intensity \( R \) a power law relation of the form \( R = c \times Z^d \) is used in radar hydrometeorology. This is the second important step for quantitative radar rainfall processing. The coefficients \( c \) and \( d \) quantify the relation and are obtained by regression on pairs of \( R \) and \( Z \) values which are calculated on ground measured DSD. The \( R-Z \) relation is highly variable. Battan (1973) lists 69 \( R-Z \) relations of different event type and climatologic regions. Atlas et al. (1999) among others report about variations of DSD and their related parameters within single events. Doviak & Zrnic (1995) and Lee & Zawadzki (2006) quantify the error on derived radar rainfall which is induced by using a single \( R-Z \) relation compared to the event wise DSD variability at the magnitude of 30% to 40%. To demonstrate these influences and their hydrological relevance, three event specific \( R-Z \) relations are plotted in Figure 6. March 6, 2003 \((c = 0.0264; d = 0.692)\) is typical for evenly distributed, stratiform rainfall, while the two \( R-Z \) relations for June 8, 2003 characterize convective rainfall for different rainfall process phases within the event (convective phase: \( c = 0.0092; d = 0.744 \) / stratiform phase: \( c = 0.0191; d = 0.684 \)). The high non-linearity involved in the \( R-Z \) scaling is stressed by the exponential increase of rainfall intensity with increasing reflectivity, especially beyond 30 dBZ. Generally, \( R-Z \) relations typical for stratiform rainfall (March 6), which are reduced to maximum reflectivity at the magnitude of 40 dBZ, only generate higher rainfall intensities for a given \( Z \) than convective event types (June 8). The two relations for June 8 demonstrate that the variability during the event induces further uncertainty. Since it is not possible to account for the temporal and spatial variability of the DSD, the coefficients for the \( R-Z \) relation have been calculated as event means \((c = 0.0152; d = 0.707)\) observed at the location of the disdrometer (Figure 1).

Figure 5 | PPI June 8, 2003 12:55 UTC; left: measured reflectivity \( Z_a \); middle: attenuation corrected reflectivity \( Z_{\text{cor}} \); right: attenuation difference \( A_{\text{Dif}} \). Subscribers to the online version of Water Science and Technology can access the colour version of this figure from http://www.iwaponline.com/wst.
However, the most important conclusion that can be drawn from Figure 6 is that the radar signal attenuation is the main cause for radar rainfall underestimation and uncertainty. Attenuation at the magnitude of 3 dB may easily result in an underestimation of intensity at the magnitude of 20 mm/hr. Since corrections up to 20 dB as in Figure 5 may be requisite, it must be concluded that especially in convective situations the signal attenuation accounts to a higher degree for radar rainfall uncertainty than the $R-Z$ relation.

### Radar—rain gauge comparison

With application of radar rainfall as direct model input the assessment of the quantitative radar processing for the target figure rainfall is of central relevance. For validation of the proposed correction procedure rainfall observed by a network of 37 ground gauges (Figure 1) was used as independent reference for the assessment of the corresponding radar rainfall. In Figure 6 (right) radar rainfall (event totals) is plotted against gauge rainfall for June 8, 2003. The conversion of the radar reflectivity into rainfall intensity was done using the event mean $R-Z$ relation given in Figure 6 for the uncorrected ($Z_a$) as well as the corrected reflectivity ($Z_{cor}$). A notable underestimation of radar rainfall against the gauge observations is obvious for the uncorrected data $Z_a$. The gradient of the regression based on the 37 pairs corresponding rainfall totals is $m = 0.34$. In case of perfect agreement $m$ would equal one.

The attenuation correction of the reflectivity fields generates a clear improvement of the radar estimates in average. The gradient is found to be $m = 0.94$. In addition, 48% of the comparisons are found within the 25% agreement limits (dotted lines) and most of the others are close to the agreement limits. When radar rainfall is compared with gauge recordings it has to be mentioned, that the results are affected by various influences such as instrumental limits of the tipping buckets (La Barbera et al. 2002; Upton & Rahimi 2003) different measuring volumes (Austin 1987) and variation of the vertical reflectivity profile. In addition atmospheric influences such as bright band effects (Joss & Waldvogel 1990; Rico-Ramirez & Cluckie 2007), anomalous propagation, as well as radar calibration, beam shielding effects and sampling errors (Rico-Ramirez et al. 2007) may have a negative impact on the comparisons which, however, have not been observed for the analyzed events.

### Relevance of correction for rainfall forecasting

To analyse the effect and benefit of the new data processing methodology on the performance of radar rainfall forecasts the HYRATRAC model was applied to generate rainfall forecasts using pattern recognition and extrapolation techniques. HYRATRAC was developed to operate in a compound model structure consisting of hydrologic and hydrodynamic models for rainfall runoff simulation and prediction and optimisation modules for RTC of urban drainage systems. Forecasts were generated for June 8, 2003.
for the Hüllerbach catchment (Figure 1) based on the cartesian PF-product which was derived from the DX-product for the two scenarios with and without attenuation correction.

The forecast graphs in Figure 7 (left) show the cumulated rainfall forecasts made every 5 min at the time $\Delta t$ before the axis time for the scenario radar data without attenuation correction. In contrast, attenuation corrected radar data were used for the forecasts illustrated in Figure 7 (right). The 35 min forecast graph e.g. was constructed from the forecast of 3.9 mm for the interval from 12:20 to 12:25 made at 11:45 hrs., the forecast of 6.8 mm for the interval from 12:25 to 12:30 made at 11:50 hrs. (new total: 10.7 mm), etc. It is obvious that even the 15 min forecast based on uncorrected data gives only a poor indication of the rainfall to come. With attenuation corrected data the heavy rainfall is “known” at least 35 min in advance giving ample time to calculate the resulting runoff, find the appropriate control decisions to set regulators. Areal rainfall observed by the four gauges located in the catchment has been calculated and is given for comparison. The good agreement of the areal radar rainfall forecasts with the ground observations shows again the high potential of the proposed methodology to correct radar rainfall in real time.

**CONCLUSIONS**

A new methodology is proposed for the attenuation correction of C-band radar data in real time. A significant feature of the methodology is that it uses information about the variability of the attenuation coefficients. Hence, no further independent reference is needed.

It was shown that the attenuation correction is able to account for spatial differentiation depending on the current rainfall, preserves and recovers the physical structure of the rain fields reasonably. The comparison of radar rainfall with gauge recordings has demonstrated that the signal attenuation at C-band accounts for most of the underestimation and uncertainty in radar rainfall. For convective rainfall the new methodology proved quite effective while the choice $R-Z$ relation is only of minor relevance for quantitative radar rainfall estimation. Finally, it was demonstrated that the attenuation phenomenon and the associated rainfall underestimation propagate also in rainfall forecasts. The use of attenuation corrected radar data in tracking and extrapolation techniques leads to a quantitative improvement of the forecasts and an extension of reliable forecast horizons which improves the potentials of RTC.

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