Estimation of attenuation correction coefficients for an X-band weather radar using a dual frequency microwave link

S. Krämer and H.-R. Verworn

Abstract—**Radar rainfall measurements have a high potential for hydrological applications. The quantitative reliability of radar derived rainfall, however, is very poor. This is mainly due to the effect of attenuation the radar signal experiences by the intervening rainfall itself. Attenuation correction methods exist but are prone to instability. A microwave link was used to provide an estimate for the path integrated attenuation the radar signal has experienced along a path length of 29.6 km. This independent measurement served as a reference for the estimation of attenuation coefficients to correct X-band reflectivity profiles.**

Index Terms—**attenuation correction, disdrometer, microwave link, radar applications, reflectivity**

I. Introduction

Radar rainfall measurements have a high potential for hydrological applications. The quantitative reliability of radar derived rainfall, however, is very poor. For radars operating at X-band frequencies and also C-band frequencies [1] this problematic nature is mainly due to the effect of attenuation the radar signal experiences by the intervening rainfall itself. An attenuation correction algorithm was proposed by [2], hereafter HB. In [3] an alternative but equivalent formulation is given, which uses a power law relation between specific attenuation k and measured reflectivity Z of the form $k = a \times Z^b$ as a basis. The coefficients a and b are known as attenuation coefficients. For correction, assumptions about the coefficients are required before the correction is made. The estimation of these coefficients, however, is problematic, since they depend on the microphysics of the current rainfall. Typically, they are derived from scattering simulations either based on a wide range of different drop size distributions to account for different types of rainfall, or on drop size distribution measurements which can be regarded as point measurements. In both cases, the derived coefficients do not account for the variability of current rainfall and the induced attenuation along the radar beams. In practise the attenuation coefficients are uniformly applied to all radar beams and assumed to be constant for different rainfall events [4]. As a consequence, the correction is prone to instability, which occurs whenever the estimated attenuation leads to ever increasing Z values beyond any valid magnitude.

In this paper time series of path integrated attenuation (PIA) are measured with a dual frequency microwave link. The measurement is done parallel to one of the radar beams and therefore provides a reference for the attenuation the radar signal has experienced due to intervening rainfall along the path of the beam. The direct comparison of measured PIA and calculated radar attenuation using the HB approach provides the basis for systematic exploration of sensible combinations of the attenuation coefficients.

The results using the path integrated attenuation information are assessed with attenuation coefficients which have been derived from drop size distribution (DSD) measurements for the same location. Non spherical drop shapes for scattering simulations have been assumed.

II. Measurement Devices and Data

The investigation is based on a network of rainfall observing measurement devices of different types and spatial coverage. The core of this observing network is formed by an X-band weather radar and a dual frequency microwave link and is supplemented by five rain gauges and a disdrometer. A graphical overview of their relative locations is given in Fig. 1. Data have been continuously recorded for the period August 2002 and June 2003.

A. X-band radar

The X-band radar is located near the city of Essen, Germany, and is operated by Emschergenossenschaft / Lippeverband, a local water authority. The radar signal is horizontally polarised at a frequency of 9.47 GHz. For flood warning aspects the radar operates in single elevation mode with lowest elevation to monitor current rainfall, only.

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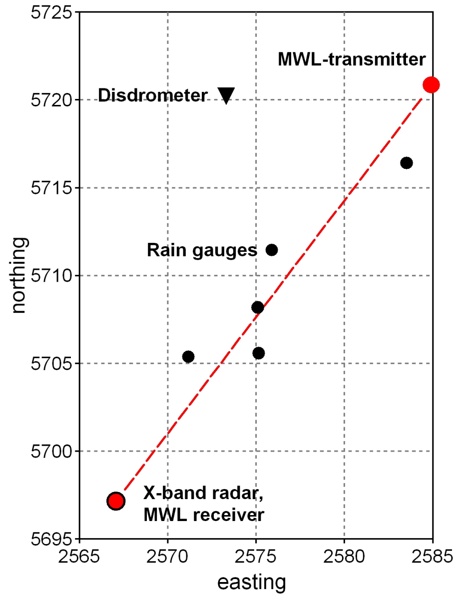

Fig. 1. Rainfall observing network. Gauss-Krueger coordinates have been used.

A complete radar scan is provided every minute. Detailed radar specifications are given in Table I.

B. *Microwave links*

The microwave link (MWL) consists of two transmitters and receivers which operate at 10.5 and 17.5 GHz. The path length of the link is 29.6 km (Fig. 1). The transmitters have been installed on a telecommunication tower at a height of 70 metres. Both receivers were directly mounted on the X-band radar tower at a height of 25 metres (Fig. 2).

The frequencies have been chosen by scattering simulations in order to obtain a linear correlation between attenuation difference of the frequencies and rain rate [5][6]. This is important for the definition of attenuation due to rainfall in section III. One objective criterion for the link design was that at least one frequency should be close to the X-band radar frequency. The transmitted signal was averaged for one minute data. Specifications of the MWL are given in Table II.

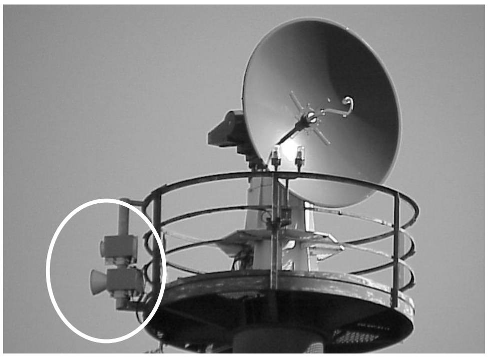

Fig. 2. X-band radar antenna and MWL receivers.

TABLE I
X-BAND RADAR SPECIFICATIONS

Signal processing	
Transmitted power	67 kW
Frequency /Wavelength	9.47 GHz (horizontal)
Pulse repetition frequency	245 Hz
Minimum detectable signal	-109 dB
Antenna	
Diameter	1.5 m
Gain	41.6 dB
Main beam width	1.1°
Elevation	0.9°
Rotation velocity	1 / min
Data processing	
Maximum range	75 km
Radial resolution, gate length	250 m
Azimuthal resolution	0.5°
Time resolution	1 min
Signal discretisation	128 classes

C. *DisdrometerRD-69*

Disdrometers measure the size diameter D and number N of raindrops. These drop size distribution (DSD) measurements N(D) dD at the ground provide an estimate for the microphysical structure of rainfall as seen by the radar aloft. Therefore, the application of scattering simulation techniques to measured DSD is a facility to define the attenuation coefficients a,b used in the correction algorithms [2].

In this investigation DSD have been observed by a disdrometer located in a distance of 8.5 km to the link path (Fig.1). The principle of the disdrometer RD-69 is based on magnetic induction and is described in [7]. The electromagnetic signals induced by raindrop impacts are converted into 20 classes of affiliated drop sizes with mean diameters in the range of D_{min} = 0.35 mm to D_{max} = 5.25 mm. The measured DSD have been sampled for 1 minute intervals.

TABLE.2 II
MICROWAVE LINK SPECIFICATIONS

Frequency	10.5 GHz (vertical)	17.5 GHz (vertical)
Dimension	400 × 290 × 190 mm	
Weight	9,0 kg	
Power input, electronic	24 V / 0.8 A	
Power input, heating	50 V /1.0 A	
Transmitted power	12 dBm	13 dBm
Lens horn antenna	250 mm	150 mm
Antenna gain	27.6 dBi	27.3 dBi

III. METHODOLOGY

A. *Definition of attenuation reference*

The exact definition of the attenuation reference derived from the MWL is of vital relevance for comparison with the radar attenuation. This has been done in two steps. First, the amount of signal attenuation due to rainfall along the link path has to be defined. To distinguish between “dry” periods with no rain and “wet” periods an approach proposed by [8] was applied. This methodology uses two indicators to define a "wet" period. One indicator is the correlation between the attenuation of the two frequencies. In case of rainfall both signals are attenuated and the correlation is high. In dry periods, however, the signal strength fluctuates randomly and the correlation is low. The second indicator consists of an independent measure of rainfall along the link. Here, the five rain gauges depicted in Fig. 1 have been chosen as rainfall sensors. Using a moving correlation window with a minimum length of 20 minutes "wet" periods are defined. A linear interpolation of the signal strength is performed in order to define a signal baseline between the 20 min "dry" intervals before and after a recognized "wet" period. Attenuation time series are then obtained as differences between the attenuated time series and the interpolated baseline.

In a second processing step a frequency scaling is required to match the attenuation characteristics of the vertical 10.5 GHz link with the horizontal 9.47 GHz radar frequency. Based on scattering simulations for different DSD, drop shapes and temperatures [9] showed that the link attenuation A_{Link} at 10.5 GHz can be scaled to the attenuation characteristics of the radar frequency with a linear factor of 0.9. This is the attenuation reference for the radar in dB

$$A_{Reference} = A_{Linkz} \times 0.9 . \quad (1)$$

*B. Radar attenuation correctio*n

The radar correction methodology which was applied in this investigation follows in principle the work by [2] but is used in a modified approach proposed by [3]. The advantage of this modification is the direct relation between specific attenuation k and reflectivity Z. Thus no conversion of rain intensity R to reflectivity Z - as in the original formulation - is required. Owing to the radar data processing the correction is implemented in a gate by gate approach. Starting from the origin of a radar beam at the radar site the attenuation for the first bin is calculated from the reflectivity value of that bin. The reflectivity of all bins beyond is then increased by this proportion. Consequently, for a given bin i of a radar beam the attenuation k_i is calculated from the measured reflectivity value (Z_i) plus the sum of attenuation from the preceding bins ($\sum k_j$). Assuming the range independent model between specific attenuation and reflectivity, $k = a \times Z^b$, the attenuation in gate i is given by

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

with l = 0.25 km length of the radar gates along the radar beam. The factor of two is to consider the two way attenuation the radar signal experiences. The radar attenuation to be compared with the reference attenuation from the microwave link then is

$$A_{Radar} = \sum_{i=0}^{118} k_i . \quad (3)$$

C. Attenuation coefficients estimation with MWL

The analysis of the attenuation coefficients is performed for each event minute by comparing $A_{Reference}$ with calculations of A_{Radar} for various combinations of the coefficients a and b. The coefficients have been varied systematically between $1 \times 10^{-5} \leq a \leq 1 \times 10^{-3}$ and $0.65 \leq b \leq 1.0$. An optimal combination of a and b is adopted when A_{Radar} and $A_{Reference}$ differ not more than ±0.25 dB

$$| A_{Radar(a,b)} - A_{Reference} | \overset{!}{\leq} 0.25 . \quad (4)$$

D. Attenuation coefficients based on DSD

For the assessment of the optimisation results with an independent reference, the link derived attenuation coefficients (a,b) may be compared with attenuation coefficients derived from the event specific DSD measurements. Therefore, the specific attenuation k and reflectivity Z of the ground measured DSD have to be calculated for the 1-minute recordings. To calculate the specific attenuation k and reflectivity Z assumptions about the drop shapes depending on its size have to be made, since the drop shape becomes increasingly oblate due to sheer stresses as the raindrops fall to the ground. As a consequence, the horizontal scattering cross section of an oblate raindrop is larger than the cross section of an equivolumetric spherical raindrop. To consider this effect drop shapes described in [10] have been assumed. The foreward ($f_{V,H}$) and backward ($S_{V,H}$) scattering amplitude matrixes have been calculated following [11]. For comparison with the horizontal radar measurement the horizontal reflectivity Z_H im $mm^6 m^{-3}$ for ground measured DSD is calculated with

$$Z_H = \frac{\lambda^4}{\pi^5 |K|^2} \times 10^{18} \int_{D_{min}}^{D_{max}} \sigma_{b,H}(D)\, N(D)\, dD \quad (5)$$

where $|K|^2$ is the refractive index of the hydrometeors. For water the refractive index is $|K|^2 = 0.93$ [12], λ in m is the wavelength of the radar, and N(D) dD is the DSD. The quantity $\sigma_{b,H}$ is the backscattering cross section in m^2 for horizontal polarisation which is obtained using the horizontal element of the back scattering amplitude S_{HH} [13]

$$\sigma_{b,H}(D) = 4\pi \left| S_{HH}(D) \right|^2 . \quad (6)$$

Parallel, the specific horizontal attenuation k_H in dB km^{-1} is given by

$$k_H = 4.343 \times 10^3 \int_{D_{\min}}^{D_{\max}} \sigma_{ext,H}(D)\, N(D)\, dD \qquad (7)$$

where the horizontal extinction cross section $\sigma_{ext,H}$ in m^2 is formulated in [13] as

$$\sigma_{ext,H}(D) = \lambda \times \mathrm{Im}\{f_{HH}(D)\}. \qquad (8)$$

Based on these k-Z values a regression has to be applied to estimate the attenuation coefficients. In terms of the linear regression on log-log scale of k_H and Z_H, the gradient of the regression line accounts for the exponent b of the power law $k = a \times Z^b$. The linear coefficient a is represented by the intercept.

IV. RESULTS

To demonstrate the results on the attenuation coefficients for different rainfall types the discussion focuses on June 8, 2003. A highly convective rain cell complex crossed the link between 12:15 and 13:00 hrs. which was followed by rainfall of stratiform character. Raindrops of maximum size $D_{max} = 5.2$ mm have been observed with a median volume diameter $D_0 > 2.0$ mm for the convective rainfall process. $A_{Reference}$ exceeded 20 dB for a period of 20 minutes (Fig. 3). A stratiform rainfall phase succeeded between 13:30 and 14:45 hrs. which was represented by small drop sizes ($D_{max} < 2.5$ mm, $D_0 = 1.3$ mm) and $A_{Reference}$ was found to be below 3 dB.

The results for the attenuation coefficients are illustrated in Fig. 4. The exponent b is plotted against the linear coefficient a. Each grey dot represents a combination of a,b which satisfies the objective criterion (4). For each minute several combinations are found which show an aligned character with a negative gradient. The “minute results” for the stratiform rainfall phase indicate a notable higher a-value with a higher negative gradient. In addition, the number of combinations is

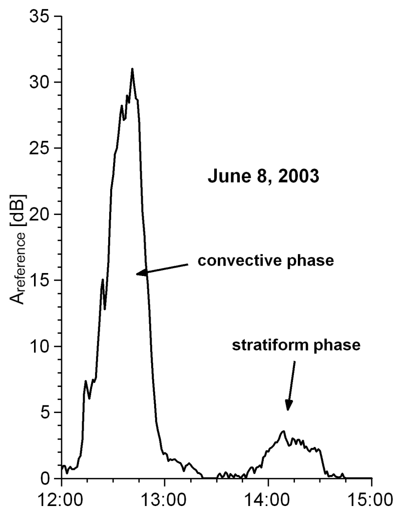

Fig. 3. Attenuation time series from microwave link.

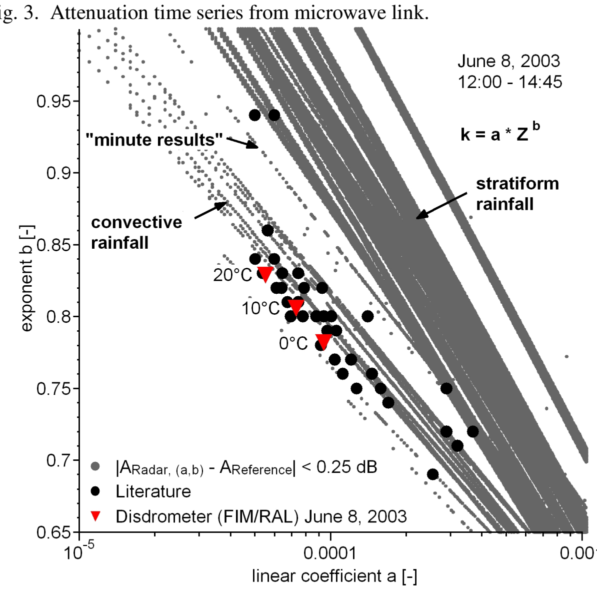

Fig. 4 Results for attenuation coefficients.

larger for the stratiform period than for the convective minutes, and there are more combinations the smaller the exponent b is. For a given exponent b values of the linear coefficient which are greater than those obtained for the “minute results” lead to overestimation of the radar attenuation. Instability of the correction is likely to occur. Lesser values underestimate the attenuation but the correction algorithm performs always stable.

The coefficient estimates based on the event measured DSD for different temperatures are shown as well as the results from a literature review [14]. A good agreement for the convective minutes is obvious. The derived coefficients, however, show a significant dependence on the rain drop temperature. This temperature is normally unknown.

V. CONCLUSION

The results demonstrate that even in situations in which the radar signal experiences high attenuation corrections the use of the HB-algorithm is possible. In this example corrections were successfully performed for path integrated one-way attenuation up to 30 dB. The enormous number of acceptable (a,b) combinations and their variability indicate that the numerical stability of the HB-algorithm is extremely sensitive to the choice of attenuation coefficients (a,b).

The characteristic and systematic behaviour of the “minute results” suggests the use of variable coefficient combinations for attenuation correction in absence of a attenuation reference and for practical application. A fixed exponent b in combination with a varying linear coefficient appears to be reasonable. Starting with a high value of the linear coefficient a, it has to be gradually reduced whenever instability occurs, until the correction becomes stable. In case of high attenuation which is characteristic for convective rainfall, the transition from instability to stability of the correction will be reached by very small decrements of the linear coefficient a.

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