Sources of error in microwave link rainfall estimation

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1 Introduction

Microwave links have been demonstrated to be higly suitable for the estimation of path-averaged rainfall intensity, both in a research setting (Ruf et al., 1996; Rincon and Lang, 2002; Holt et al., 2003; Rahimi et al., 2003, 2004; Minda and Nakamura, 2005; Krämer et al., 2005; Upton et al., 2005; Grum et al., 2005; Leijnse et al., 2007a) and from commercial cellular communication networks (Messer et al., 2006; Leijnse et al., 2007b). However, some issues must be investigated more closely before these measurements, especially from commercial cellular communication networks, can be used operationally. To assess the quality of rainfall retrieved from networks of microwave links, it is necessary to quantify errors associated with single-link measurements. This paper deals with the estimation of some of these errors in microwave link measurements.

Microwave links consist of two antennas between which an electromagnetic signal propagates. In rain, the electromagnetic signal is attenuated by the raindrops in its path (e.g. Hogg, 1968). This attenuation depends on the distribution of sizes and the number concentration of the raindrops in the signal path, and on the frequency of the signal. Hence, the relation between the measured attenuation and the rainfall intensity may depend on the type of rain. Because rain is known to be variable in both time and space (e.g. Jameson and Kostinski, 2002), this dependence may cause errors if fixed relations are used for the retrieval of path-averaged rainfall intensities from measurements of path-integrated attenuation. The temporal sampling strategies and rounding of signal powers commonly found in commercial cellular communication network monitoring (Messer et al., 2006; Leijnse et al., 2007b) also affect the errors in the retrieved rainfall intensities. Furthermore, microwave link antennas may become wet in rain. This wet antenna attenuation is known to cause excess attenuation (Minda and Nakamura, 2005; Leijnse et al., 2007a), which is an additional source of error.

In this paper we use raindrop size data measured during 3 weeks in Cabauw, The Netherlands to investigate the effect of the microstructure (i.e. related to the drop size distribution) of rainfall in a simulation framework similar to that used by Berne and Uijlenhoet (2007). The effect of the macrostructure of rainfall will be investigated using high-resolution radar data recorded during more than 1.5 years in Delft, The Netherlands. The same data set will be used to investigate the effect of the employed temporal sampling strategy, rounding of received signal powers, wet antenna attenuation, and correction for the latter phenomenon.

2 Data and methodology

2.1 Drop size data

The raindrop size data set used in this paper has been collected during the BBC2 measurement campaign. This campaign took place in May 2003 at the CESAR (Cabauw Experimental Site for Atmospheric Research) site in The Netherlands. Drop size data have been collected using a 2D Video Disdrometer (2DVD, Schönhuber et al., 1994), and additional wind data were collected as 10-minute averages at 20 m above the terrain.

A range profile of drop size distributions (DSDs) has been generated using time series of measured DSDs in combination with wind speed measurements. Taylor's hypothesis is invoked to transform the time coordinate to a spatial coordinate. Profiles of DSDs are generated with a resolution of 250 m, which in this case corresponds to time intervals between 16.3 seconds and 14 minutes (with an average of 52.5 s), depending on the wind speed.

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2.2 Radar data

The radar data that are used in this paper were recorded during more than 1.5 years (1993-1994) by the high-resolution X-band weather radar SOLIDAR. At the time this radar was located Delft, The Netherlands, and was operated by the IRCTR institute of TU Delft (see Ligthart and Nieuwkerk, 1990). The spatial resolution of this radar is 1.875° in the azimuth direction and 0.12 km in the radial direction, with a maximum range of 15.36 km. The temporal resolution is approximately 16 s.

We have selected one radial that will be used for the simulations in this paper. The effect of clutter (mostly caused by buildings in this flat area) is small for this radial. However, some clutter correction was deemed necessary, as there would otherwise be areas that have no dry periods. Dry areas on part of the selected radial may play a large role in the effect of attenuation caused by wet antennas on retrieved path-integrated rainfall (Minda and Nakamura, 2005; Leijnse et al., 2007a), as one or both antennas may be dry while there is rain on the link.

2.3 simulation of microwave link signals

Profiles of rainfall intensities and DSDs are used to compute microwave link signals and corresponding values of true path-averaged rainfall intensity. We will use two measures to evaluate the quality of the rainfall products: (1) the normalized mean bias error (MBE) as a measure of systematic errors; and (2) the normalized root mean square error (RMSE) as a measure of the uncertainty. Both of these are normalized by the global mean rainfall intensity.

The profile of DSDs is converted to profiles of R and k using the $v(D)$ relation of Beard (1976) and the T-matrix scattering computations by Mishchenko (2000), respectively. Microwave link signals and corresponding values of path-averaged R are simulated for links with different lengths using a moving window on the profile of DSDs.

The rainfall intensities R (mm h^{-1}) measured by the radar are converted to specific attenuation k (dB km^{-1}) values using a power law (see Atlas and Ulbrich, 1977)

$$R = ak^b, \tag{1}$$

where a and b depend on the employed frequency (see Leijnse, 2007, Chapter 5). The same relation is used in the retieval of path-averaged rainfall intensities from path-averaged attenuation values.

3 Results and discussion

3.1 Errors caused by rainfall microstructure

Figure 1 shows the normalized MBE and RMSE as functions of link length and frequency based on the drop size data (see Section 2.1). There is a clear optimum in frequency around 40 GHz, where the bias is close to zero and the uncertainty has a minimum. This optimum is close to the frequency where the $R-k$ relation (see Eq. (1)) is linear (i.e. $b = 1$, at 36 GHz), and it is nearly independent of the length of the link. If the link frequency deviates significantly from this optimal frequency (i.e. more than $\sim$ 20 GHz), the errors and uncertainties may become quite severe.

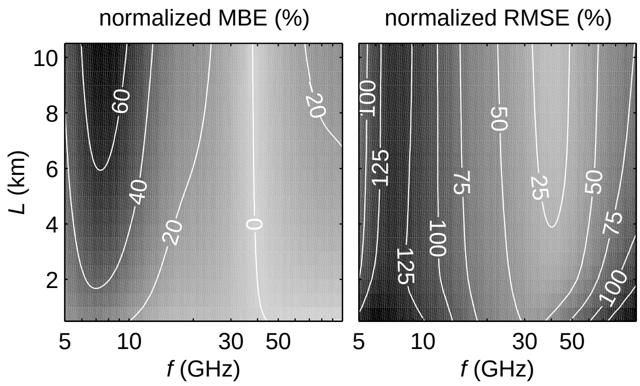

Fig. 1. Errors and uncertainties in microwave link rainfall retrievals as a result of variations in the microstructure of rain as a function of link length (L) and frequency (f). Shown are normalized MBE (left) and normalized RMSE (right).

3.2 Errors caused by rainfall macrostructure

Figures 2 and 3 show the normalized MBE and RMSE, respectively, that result from the macrostructure of rainfall. These figures are based on simulations using radar data (see Section 2.2). In these figures, the effect of the temporal sampling strategy and the rounding of received signal powers can be seen. The temporal sampling strategies can be characterized as follows:

- *Continuous.* The link signal is converted to a rainfall intensity at every timestep, after which these values of R are averaged over 15 minutes. This is common when using research microwave links (e.g. Ruf et al., 1996; Rincon and Lang, 2002; Rahimi et al., 2003; Leijnse et al., 2007a).

- *Averaged.* The link signal is averaged over 15 minutes, after which this time average is converted to a value of R. This is common in commercial cellular communication link monitoring (Messer et al., 2006).

- *Intermittent.* The link signal is sampled only once every 15 minutes, in the middle of the averaging periods mentioned above. This is also encountered in commercial cellular communication link monitoring (Leijnse et al., 2007b).

The figures show that of the temporal sampling strategies used in cellular communication network monitoring,

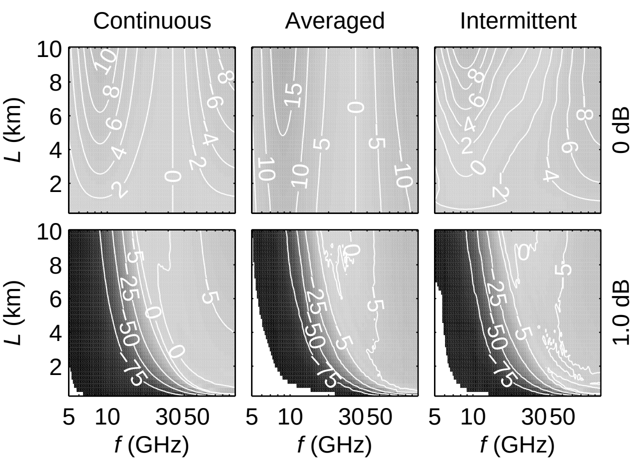

Fig. 2. Errors (normalized MBE) in microwave link rainfall retrievals as a result of variations in the macrostructure of rain as a function of link length (L) and frequency (f). The effects of different temporal sampling strategies can be seen (left to right) as well as the effect of rounding of received signal power (top and bottom).

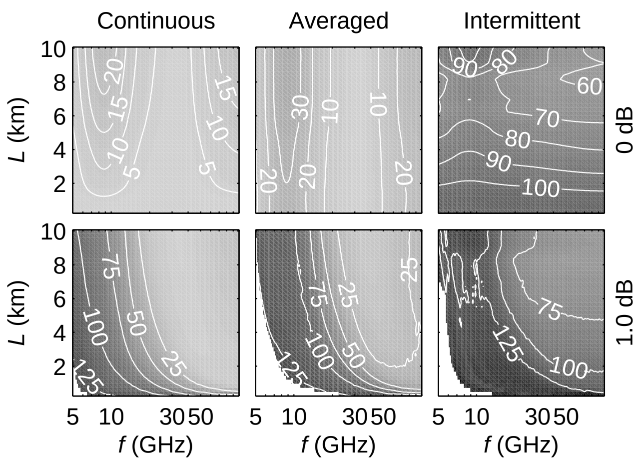

Fig. 3. Uncertainties (normalized RMSE) in microwave link rainfall retrievals as a result of variations in the macrostructure of rain as a function of link length (L) and frequency (f). The effects of different temporal sampling strategies can be seen (left to right) as well as the effect of rounding of received signal power (top and bottom).

the averaged strategy is to be preferred (because of the very high RMSE for the intermittent strategy). The effect of the rounding of received signal powers is highly dependent on both the frequency and length of the link. This is because the specific attenuation is an increasing function of frequency, and the total attenuation at a given path-averaged rainfall intensity is simply larger for longer links. The relative effect of rounding is of course lower at higher total attenuations. If the link frequency is carefully chosen and the link is not too short (longer than ∼3 km), errors and uncertainties remain limited for the continuous and the averaged sampling strategies.

3.3 Errors caused by wet antenna attenuation

We have simulated the effect of wetting of antennas by assuming that a perfectly flat film of water is formed on the material covering the antennas. The thickness of this film is assumed to be related to the local rainfall intensity via a power law, of which the coefficient and exponent have been calibrated based on experimental microwave link and rain gauge data (for details regarding the experiment, see Leijnse et al., 2007a). Normalized MBE and RMSE have again been computed from simulations carried out using the radar data set (see Section 2.2).

Figure 4 shows the resulting normalized MBE (top) and RMSE (bottom) as functions of link length and frequency for the continuous sampling frequency without considering the effect of rounding errors. The effect of wet antenna attenuation and its correction can also be seen in this figure. Correction has been carried out by simply inverting the relation that is used to compute the wet antenna attenuation, but now using the *path-integrated* attenuation. It is apparent that wetting of antennas is disastrous for the quality of retrieved rainfall for nearly all link lengths and frequencies. However, if corrections for this phenomenon are applied, the errors and uncertainties remain within reasonable bounds, especially near the optimal frequency.

4 Conclusions

We have used drop size data as well as radar data measured in The Netherlands in a simulation framework to investigate the errors and uncertainties in microwave link rainfall retrievals as functions of the employed link length and frequency. The effects of the microstructure and macrostructure of rainfall, as wel as the influence of the temporal sampling strategy, rounding of received signal powers, and wetting of antennas have also been studied.

It is clear from the simulation results that the employed link frequency should be around 40 GHz (with a margin of ∼ 20 GHz either way), and that the link should not be too short (> 3 km). If these conditions are met, the effects of averaging the received signal power over 15 minutes and of rounding this power to the nearest dB are limited. Taking one sample only once every 15 minutes greatly deteriorates the quality of the retrieved rainfall, and is therefore discouraged. The effect of wetting of the antennas has been shown to be large. However, if a correction for this phenomenon is applied, the errors and uncertainties are limited in the optimal frequency range.

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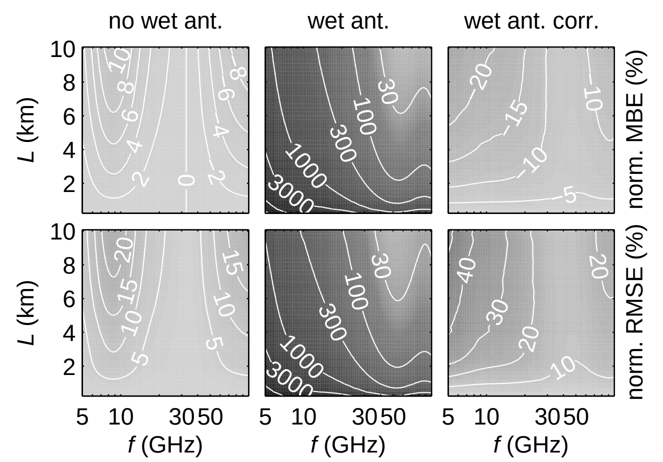

Fig. 4. Errors and uncertainties in microwave link rainfall retrievals as a result of variations in the macrostructure of rain as a function of link length (L) and frequency (f). Shown are normalized MBE (top) and normalized RMSE (bottom). The effects of wetting of antennas and correction for this can be seen (left to right). Grey scale is logarithmic for errors and uncertainties $> 50\%$. Note that the top and bottom left panels are the same as the top-left panels in Figs 2 and 3, respectively.

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