

Measuring urban rainfall using microwave links from commercial cellular communication networks

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[1] The estimation of rainfall using commercial microwave links is a new and promising measurement technique. Commercial link networks cover large parts of the land surface of the earth and have a high density, particularly in urban areas. Rainfall attenuates the electromagnetic signals transmitted between antennas within this network. This attenuation can be calculated from the difference between the received powers with and without rain and is a measure of the path-averaged rainfall intensity. This study uses a 17-day data set of, on average, 57 single-frequency links from 2009 to estimate rainfall in the Rotterdam region, a densely populated delta city in Netherlands ($\approx 1250 \text{ km}^2$, >1 million inhabitants). A methodology is proposed where nearby links are used to remove signal fluctuations that are not related to rainfall in order to be able to reliably identify wet and dry weather spells. Subsequently, received signal powers are converted to path-averaged rainfall intensities, taking into account the temporal sampling protocol and attenuation due to wet antennas. Link-based rainfall depths are compared with those based on gauge-adjusted radar data. In addition, the rainfall retrieval algorithm is applied to an independent data set of 21 rainy days in 2010 with on average 16 single-frequency links in the same region. Rainfall retrievals are compared against gauge-adjusted radar rainfall estimates over the link path. Moreover, the retrieval algorithm is also tested using high-resolution research link data to investigate the algorithm's sensitivity to temporal rainfall variations. All presented comparisons confirm the quality of commercial microwave link data for quantitative precipitation estimation over urban areas.

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1. Introduction

[2] Urban hydrology requires rainfall observations with high spatial and temporal resolution [e.g., *Berndtsson and Niemczynowicz*, 1988]. Weather radars are in principle well-suited for that purpose, but often need adjustment. Usually only a few rain gauge measurements are available as input for hydrological models or to adjust radar data in real time. The estimation of rainfall using microwave links from commercial cellular communication networks is a new and potentially valuable source of information. Such networks cover large parts of the land surface of the earth and have a high density. The principle of rainfall estimation using microwave links is that electromagnetic signals transmitted from one antenna to another are attenuated by rainfall. Raindrops absorb part of the incident wave and, in addition, scatter some of the energy out of the beam. Attenuation resulting from scattering and absorption increases with increasing microwave frequency. The attenuation of electromagnetic signals also becomes larger for an increasing number and size

of the raindrops present along the beam. By measuring the received power at one end of a microwave link as a function of time, the attenuation due to rainfall can be calculated. These received powers are a by-product of the communication between mobile telephones and are, in general, only used to monitor the stability of the link connection. *Messer et al.* [2006], *Leijnse et al.* [2007b], and *Zinevich et al.* [2009] have shown that average rainfall intensities over the length of a commercial single-frequency microwave link can be derived from the attenuation. This makes commercial microwave link networks promising for measuring rainfall with a high temporal resolution, which is particularly important in urban areas.

[3] An illustration of the ability of a microwave link to measure intense rainfall is given by *Brauer et al.* [2011]. On 26 August 2010, the eastern part of Netherlands was struck by heavy rainfall. A link from the same cellular communication network ($f = 15.3 \text{ GHz}$, $L = 15.1 \text{ km}$) as used in this study kept functioning for 93% of the time for a path-averaged gauge-adjusted daily radar rainfall depth of 111 mm. The connection even remained stable during the maximum mean 15 min path-averaged radar rainfall intensity of 30 mm h^{-1} on this day. In contrast, an automatic rain gauge stopped recording and missed several hours of rain, apparently due to instrumental problems caused by the intense rainfall. Note that particularly the daily accumulations were extreme, whereas the rainfall intensities were not that extreme. A

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lower data availability due to rainfall will only occur for very high rainfall intensities.

[4] The focus of this paper is to estimate accurate path-averaged rainfall intensities from data of a network of commercial microwave links. Some attention is given to the estimation of areal rainfall. The generation of rainfall maps is beyond the scope of the current study. The interested reader is referred to, for instance, Zinevich *et al.* [2008], Goldshtein *et al.* [2009], Zinevich *et al.* [2009], and Overeem *et al.* [2011]. Note that most of the precipitation in Netherlands that reaches the earth's surface is rainfall, with occasional hail in summer thunderstorms and some snow and hail events in winter [Leijnse *et al.*, 2010b].

[5] Data sets from a commercial microwave link network over an urban area in Netherlands, the Rotterdam region ($\approx 1250 \text{ km}^2$), are available: A calibration data set of 17 days, of which 7 experienced rain ($>1\%$ rainy periods per day averaged over all links), in June and July 2009 for on average 57 single-frequency links, and a validation data set of 21 rainy days for on average 16 single-frequency links from 2010. This is one of the largest commercial microwave link data sets described in the literature so far (3014 h of rainfall).

[6] A methodology is proposed to derive rainfall intensities and rainfall depths from the received signal level data, which are minimum and maximum received powers over each 15 min period. This simple method can be applied in an operational setting, which is different from previous studies. The first step is to correct the received signal powers for fluctuations not related to rainfall, which can be quite strong during dry weather conditions. A novel, link-based approach is developed in which a mutual decrease in minimum received powers of nearby links is employed to identify wet spells. Another approach proposed here is the use of weather radar data to identify wet and dry weather conditions. In the second step the reference signal level is determined. In the third step a new methodology is proposed to convert the signal powers to average rainfall intensities, where the temporal sampling protocol and attenuation due to wet antennas is taken into account. The magnitude and dynamics of the link-based rainfall accumulations are compared with those obtained from gauge-adjusted radar data. In addition, a research link with high temporal resolution is used for testing the proposed rainfall retrieval algorithm. Finally, the viability of using microwave link data from commercial cellular telecommunication networks for quantitative rainfall estimation is discussed.

[7] In section 2 the commercial and research microwave link, radar, and rain gauge data are described. Section 3 describes the methodology to derive link-based rainfall intensities. An extensive test of the rainfall retrieval algorithm is given in section 4. Finally, in sections 5 and 6 a discussion and conclusions are provided.

2. Data

2.1. Commercial Microwave Link Data

[8] Received signal level data were obtained from a commercial microwave link network in the Rotterdam region, a densely populated urban area in Netherlands (>1 million inhabitants) and a delta city located near the outlets of the rivers Rhine and Meuse. All links for which both

transmitter and receiver are within a 20 km radius from the Rotterdam city center (i.e., in an area of approximately 1250 km^2), and which have a minimum daily (8–8 UTC) data availability of 83.3% (i.e., 20 h per day) for a given day and 25.0% (i.e., 6 h per day) for the previous day were selected. Only links with a length larger than 0.7 km are considered. This results in on average 57 links for 17 days in June and July 2009, a calibration data set (CAL 2009), and on average 16 links for 21 days in 2010 (April, May, July, and August), either completely used as a calibration data set (CAL 2010) or completely used as a validation data set (VAL 2010). Figure 1 displays the locations of the employed commercial microwave links, which are single-frequency links transmitting vertically-polarized signals. Links between a 20 and 30 km radius from the Rotterdam city center were also selected according to the same criteria, but are only used in the link approach to identify wet and dry spells (this will be addressed later in section 3.2). These are not displayed in Figure 1.

[9] The available data sets contain minimum and maximum received powers over 15 min intervals with a resolution of 0.1 dB, based on 10 Hz sampling. The average spatial density of the network is 0.10 km of microwave link length per km^2 , and the average link length is 3.7 km. Note that these links represent only part of the microwave link network of one of the providers in the Netherlands. Tables 1 and 2 give the number of selected links, the average data availability, and the percentage of rainy periods for each day for the CAL 2009 and 2010 data set, respectively. The average data availability of the selected links is 91% for the CAL 2009 data set and 98% for the 2010 data set. The percentage of rainy periods (averaged over all links) for the CAL 2009 data set, 4%, is clearly lower than that for the VAL 2010 data set, approximately 25%. This percentage is calculated from the number of 15 min periods with a link rainfall intensity larger than zero. The CAL 2009 and the 2010 data sets contain 3014 h of rainfall, which is based on these numbers.

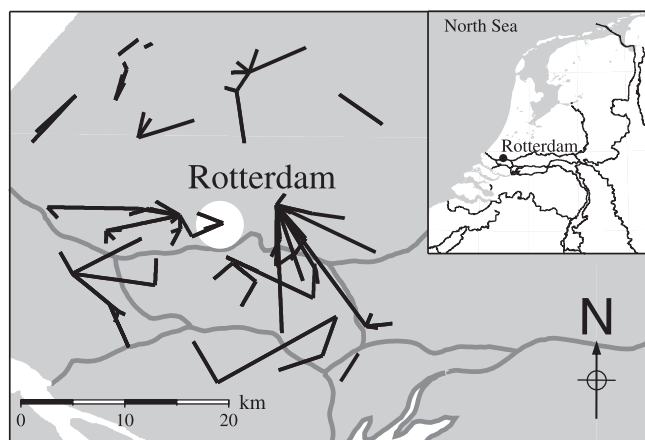


Figure 1. Map of the Rotterdam region with the locations of the employed commercial microwave links (black lines), the city center of Rotterdam (white circle), and the rivers (gray lines). The inset is a map of Netherlands with the location of Rotterdam.

Table 1. Characteristics of the Commercial Microwave Link CAL 2009 Data Set^a

Date	Number of Selected Links	Average Data Availability	Rainy Periods
13 Jun 2009	61 (58)	97%	0%
14 Jun 2009	61 (58)	97%	8%
15 Jun 2009	61 (58)	88%	10% (11%)
16 Jun 2009	61 (58)	92%	9% (10%)
20 Jun 2009	59 (56)	88%	0%
21 Jun 2009	61 (58)	93%	2% (1%)
22 Jun 2009	61 (58)	97%	0%
23 Jun 2009	53 (51)	85%	0%
24 Jun 2009	35 (32)	85%	0%
25 Jun 2009	55 (52)	85%	0%
2 Jul 2009	60 (57)	89%	0%
3 Jul 2009	62 (59)	97%	0%
4 Jul 2009	62 (59)	93%	2%
5 Jul 2009	62 (59)	93%	0%
6 Jul 2009	50 (49)	85%	1%
7 Jul 2009	58 (55)	86%	13%
8 Jul 2009	50 (47)	85%	26% (28%)
Average	57 (54)	91%	4%

^aIn parentheses, if they differ from the radar approach, the characteristics for the link approach.

[10] The frequencies of the microwave links range from approximately 13 to 39 GHz. The links typically measure at a height of several tens of meters above the ground. Figure 2 shows the frequency versus the corresponding link length for the commercial links in this study. In general, the frequency decreases for increasing link lengths. This is because longer links require reduced specific attenuations due to rainfall, which is obtained for lower frequencies.

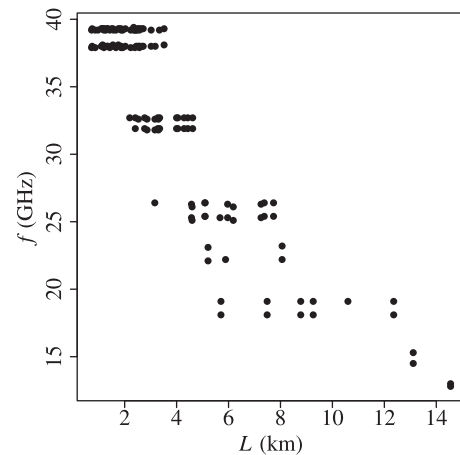
2.2. Research Link Data

[11] Data were obtained from a 27 GHz research link. The research link data are used for testing how well the

Table 2. Characteristics of the Commercial Microwave Link 2010 Data Set^a

Date	Number of Selected Links	Average Data Availability	Rainy Periods
1 Apr 2010	34 (31)	96%	34% (37%)
4 Apr 2010	33 (29)	98%	34% (31%)
30 Apr 2010	26 (23)	98%	13% (16%)
2 May 2010	27 (24)	97%	19% (15%)
3 May 2010	25 (20)	99% (97%)	41% (61%)
4 May 2010	23 (20)	98%	23% (19%)
12 May 2010	26 (23)	98%	44% (33%)
15 Jul 2010	21 (17)	98%	12% (11%)
28 Jul 2010	18 (15)	98%	12%
8 Aug 2010	15 (13)	98%	22% (24%)
11 Aug 2010	9 (4)	98%	16% (34%)
13 Aug 2010	7 (3)	98%	7% (5%)
14 Aug 2010	7 (3)	98%	8% (10%)
16 Aug 2010	8 (3)	98%	32% (29%)
18 Aug 2010	8 (3)	98%	13% (32%)
23 Aug 2010	6 (3)	98%	21% (28%)
25 Aug 2010	10 (4)	99% (98%)	9% (6%)
26 Aug 2010	7 (3)	98%	41% (45%)
27 Aug 2010	11 (7)	98%	29% (36%)
29 Aug 2010	9 (7)	98% (97%)	27% (28%)
30 Aug 2010	10 (4)	98%	29% (28%)
Average	16 (12)	98%	25% (27%)

^aIn parentheses, if they differ from the radar approach, the characteristics for the link approach.

**Figure 2.** The frequency of the microwave link f (GHz) plotted against its length L (km) for the commercial links used in this study (see Figure 1).

proposed rainfall retrieval algorithm deals with the temporal sampling strategy of the commercial links. The link and accompanying rain gauge data set have been described in *Leijnse et al.* [2007a]. This 27 GHz research link, with a power resolution of 0.04 dB, was located between the towns of Rhenen and Wageningen (4.89 km), in the middle of Netherlands. Data from, at most, five rain gauges were used to estimate path-averaged 15 min rainfall intensities. The link data were reprocessed, resulting in received powers based on 10 Hz sampling, from which minimum and maximum received powers were derived for each 15 min interval. In addition, true mean (based on 10 Hz), minimum and maximum path-averaged rainfall intensities were estimated. Attenuation due to wet antennas was removed using the same approach as in *Leijnse et al.* [2007a], which resulted in a coefficient of determination of 0.93 for path-averaged event totals from rain gauges and the microwave link. Wet spells were identified by selecting all intervals for which an estimated path-averaged rainfall intensity of at least 0.8 mm h^{-1} in 15 min, corresponding with one tip, had been measured by the rain gauges. The reference signal level is the signal power in the absence of rain scatter. For each day, the reference signal level was calculated as the median of the received powers during dry weather conditions, for which the rainfall intensity was below 0.8 mm h^{-1} . Data were obtained in this manner for 20 days from 29 May to 20 July 1999.

2.3. Radar Data

[12] The relatively low density of operational rain gauge data in Netherlands, especially for subdaily durations (≈ 1 gauge per 1000 km^2) and in urban areas, limits its suitability to verify link-based rainfall intensities or accumulations. For this reason, a radar data set of path-averaged rainfall intensities over each link was constructed. Almost the same procedure was followed as in *Overeem et al.* [2009a, 2009b] to obtain composites of gauge-adjusted rainfall depths, the main difference being the spatial resolution, which was increased from 2.4 to 1 km.

[13] Data were obtained from the two, C-band, Doppler weather radars in Netherlands, operated by Royal Netherlands

Meteorological Institute, for the selected 38 days. Horizontal cross sections of the radar reflectivity factor at a constant altitude (pseudo-CAPPI images) of 1500 m were utilized with a 5 min sample time interval. The reflectivity data from both radars were combined into one composite using a weighing factor as a function of range from the radar. The radars are located in Netherlands in De Bilt (52.10°N, 5.18°E, 44 m above mean sea level) and Den Helder (52.96°N, 4.79°E, 51 m above mean sea level). After ground clutter removal [Holleman and Beekhuis, 2005], the influence of remaining strong residual clutter and hail was limited by setting reflectivities above 55 to 55 dBZ ($\approx 100 \text{ mm h}^{-1}$). Next, reflectivity factors Z ($\text{mm}^6 \text{ m}^{-3}$) were converted to rainfall intensities R (mm h^{-1}) with a fixed Z - R relationship [Marshall et al., 1955], $Z = 200R^{1.6}$, resulting in 97 levels of rainfall intensities ranging from 0.1 to 100 mm h^{-1} , from which 5 min rainfall data and 1 h rainfall depths were derived if at least 10 images were available in the corresponding hour. A five-pixel median filter on nearest-neighbor pixels was applied to the depths to remove local outliers caused by accumulated residual ground clutter. The data availability is close to 100% for the CAL 2009 as well as the 2010 data set.

[14] Rain gauge networks were utilized to adjust the radar-based accumulations: an automatic network with 1 h rainfall depths for each hour (≈ 1 station per 1000 km^2) and a manual network with 24 h 08–08 UTC rainfall depths (≈ 1 station per 100 km^2). A daily spatial adjustment was combined with an hourly mean-field bias adjustment. Overeem et al. [2009a, 2009b] give a more detailed description of the radar and rain gauge data set and the employed adjustment methods. They show that the adjustment procedures result in a high-quality radar rainfall data set, which is suitable to derive extreme rainfall statistics [see also Overeem et al., 2010].

[15] Subsequently, path-averaged rainfall intensities were derived from the radar pixels covering each link path for each 5 min time step. The mean 15 min radar rainfall intensity over a link was calculated by averaging the three 5 min path-averaged radar rainfall intensities. Cumulative rainfall depths, over different aggregation periods (up to daily), were calculated from these mean 15 min radar rainfall intensities. In a similar manner, these mean 15 min rainfall intensities were also derived for the unadjusted radar data, where no five-pixel median filter on nearest-neighbor pixels was applied and no rain gauges were used to adjust the data (comparable to operational radar rainfall intensities). These unadjusted radar rainfall intensities were only used in the classification of wet and dry spells (the radar approach in section 3.2). Unadjusted instead of adjusted rainfall intensities were chosen because of their real-time availability, making them useful for application in an operational link-based rainfall product.

3. Methodology

3.1. Introduction

[16] Commercial microwave links are widely used in mobile telecommunication. Along such links electromagnetic waves are sent from an antenna at one tower to an antenna at another tower. The waves are sent in a beam, of

which the main lobe is a narrow cone widening as it leaves the transmitter [Upton et al., 2005].

[17] The rainfall intensity at a point can be estimated from the specific attenuation k (dB km^{-1}) of a microwave signal using a power law, the R - k relation [Atlas and Ulbrich, 1977]:

$$R = ak^b, \quad (1)$$

where R is the rainfall intensity (mm h^{-1}). The coefficient a and exponent b depend on the frequency, polarization, temperature, water phase, and, if liquid, on the drop size distribution, drop shape, and canting angle distribution [Jameson, 1991; Berne and Uijlenhoet, 2007; Leijnse et al., 2010a]. For a microwave link, the relative decrease in microwave signal power is related to the attenuation A_m (dB) over the link with length L (km), and thus to the rainfall intensity:

$$P_{\text{ref}}(L) - P(L) = A_m = \int_0^L k(s) ds = \int_0^L \left[\frac{R(s)}{a} \right]^{1/b} ds, \quad (2)$$

where P stands for received signal power (dBm), with P_{ref} the reference signal level or baseline, and s the distance along the link (km). These integrals have to be approximated because $R(s)$ cannot be derived from the scalar P . To be able to derive rainfall intensities from received signal powers, it is assumed that the R - k relation for the point scale provides a good approximation for the path-averaged rainfall intensity $\langle R \rangle$ (mm h^{-1}) as well:

$$A_m = L \langle k \rangle \approx L \left(\frac{\langle R \rangle}{a} \right)^{1/b}, \quad (3)$$

where $\langle k \rangle$ is the path-averaged (specific) attenuation (dB km^{-1}), so that $\langle R \rangle$ can be expressed as

$$\langle R \rangle = a \left[\frac{P_{\text{ref}}(L) - P(L)}{L} \right]^b. \quad (4)$$

Values of a and b used in this study are those derived from measured drop size distributions by Leijnse et al. [2008]. Figure 3 (left) shows that the value of the exponent b is close to 1 for the frequencies employed in this study, which range from 13 to 39 GHz. Because of this near linearity the approximation in equation (3) will not suffer from large errors, as is shown by Berne and Uijlenhoet [2007] and Leijnse et al. [2008]. Appendix A shows this assumption can also be assessed using a Taylor series expansion. In case the spatial rainfall variability, in terms of the coefficient of variation of k along the link (CV_k), becomes large, only a slight overestimation is found for the lowest frequency, 13 GHz, and some underestimation for the highest frequency, 39 GHz (Figure 3, right). Although this error is systematic, i.e., an overestimation or underestimation is found depending on the link frequency, determining the size of this error is not straightforward. It strongly depends on the magnitude of the spatial rainfall variability along the link. Since the strength is only measured at one end of a link it is difficult to obtain an accurate estimate of CV_k in an operational context.

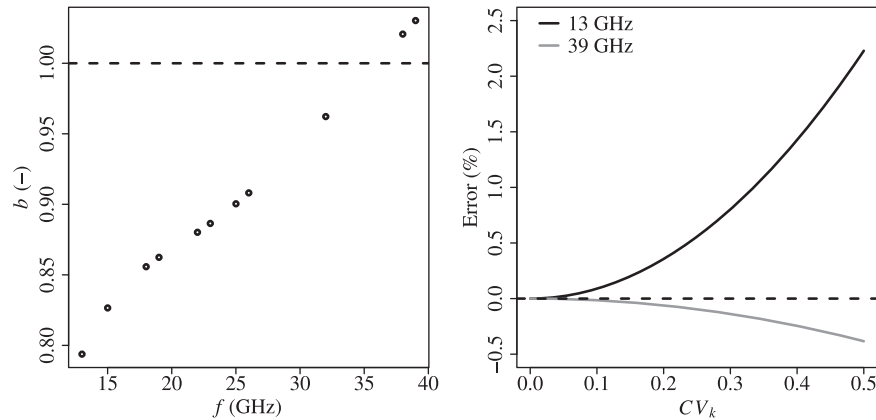


Figure 3. The value of the exponent b as a function of the frequency f (GHz) of the microwave signal for (left) the commercial links used in this study. Estimated errors in rainfall intensities due to neglecting spatial variability in k for a range of values of CV_k for (right) the lowest and highest frequency used in this study.

[18] *Berne and Uijlenhoet* [2007] investigate the influence of frequency, link length, and spatial variability of the drop size distribution along the path of the link, on the retrieved path-averaged rain rates for frequencies of 5 to 50 GHz and link lengths of 0.5 to 30 km. They show that a and b of equation (4), i.e., the coefficients of the link-averaged R - k relation, mainly depend on frequency and much less on link length. *Goldshtein et al.* [2009] and *Zinevich et al.* [2009, 2010] account for spatial rainfall variability along the link.

[19] Several other sources of error have been encountered in estimating rainfall intensities using microwave links. Signal fluctuations not related to rainfall often occur and need to be removed so that a reliable classification of wet and dry spells is obtained. Related to this, an appropriate reference signal level or baseline has to be chosen, based on the received signal powers during dry weather conditions. Signal fluctuations not related to rainfall can be caused by dew formation on the antennas, the varying absorption by atmospheric constituents (particularly by water vapor around 22 GHz), refraction and reflection of the beam, ducting, multipath, scintillation, antenna icing, and interference by other systems [*Upton et al.*, 2005]. According to *Upton et al.* [2005] the variations in magnitude of the received signal during dry weather are in general small compared to the variations during rain, which is confirmed by this study. However, occasionally a very large and short-lasting (shorter than 15 min) decline in the received power is found during dry weather conditions.

[20] Another source of error is overestimation of the attenuation because part of the decrease in microwave signal power is caused by water films on the antennas. This wet antenna attenuation due to rainfall is an important error source, for which a correction should be applied [*Kharadly and Ross*, 2001; *Minda and Nakamura*, 2005; *Leijnse et al.*, 2007a, 2007b, 2008]. Longer links are expected to be less vulnerable to wet antenna attenuation, because the attenuation due to rainfall along the link is relatively large with respect to the wet antenna attenuation and because the probability of one or two dry antennas is larger [*Leijnse et al.*, 2008]. Furthermore, the resolution of stored signal powers can be as low as 1 dB, which deteriorates the accuracy of

estimating small rainfall intensities [*Zinevich et al.*, 2009] and is especially important in case of short links and in case of low sensitivity due to low link frequency [*Leijnse et al.*, 2008]. This is hardly an issue in this study since the power resolution of the link data is 0.1 dB.

[21] The temporal sampling strategy or protocol determines the number of available samples per unit of time and the applied methodology to obtain these samples. *Leijnse et al.* [2008] investigate the influence of different temporal sampling strategies: continuous, averaged, and intermittent. The latter two strategies are usually employed in commercial cellular communication link monitoring: The signal powers are averaged over 15 min or sampled only once in the middle of the 15 min period. A third important temporal sampling strategy has been utilized for the commercial data used in this study, being similar to the one in *Messer et al.* [2006]: the minimum and maximum received signal powers, P_{\min} and P_{\max} , are available over 15 min intervals. This and the intermittent strategy will lead to sampling errors, because the temporal variability of rainfall intensities can often be large.

[22] Another possible error is a decreased data availability of received signal levels due to heavy rainfall. Most microwave links are designed to operate at least 99.99% of the time. The lower data availability in this study can be mainly attributed to storage problems at the communication company's server. Hence, our usage of the term "data availability" has hardly nothing to do with the functioning (or not) of microwave links as such.

[23] Sections 3.2–3.4 will deal with corrections for the sources of error which are expected to be most important for the commercial link data sets in this study: signal fluctuations not related to rainfall, wet antenna attenuation, and the temporal sampling strategy.

3.2. Classification of Wet and Dry Spells

[24] The first step in the rainfall retrieval algorithm is to develop a reliable classification methodology between wet and dry spells. An approach is proposed in which a 15 min interval is labeled wet if the mutual decrease in minimum received powers of nearby links in the same interval exceeds two thresholds (called "the link approach"

hereafter). The basic reasoning behind this approach is that rainfall, and hence received signal powers, are correlated in space. The spatial correlation of rainfall intensities along nearby links is expected to be large enough to justify this approach. A step-by-step description of the classification algorithm is given in Appendix B.

[25] The other approach is to use radar data to identify wet and dry weather conditions (called “the radar approach” hereafter). For each link and time step the path-averaged mean 15 min rainfall intensity along the link from unadjusted radar data is used. If this intensity is larger than 0.1 mm h^{-1} , the current and subsequent time step are classified as wet. Since the radar measures at larger heights, it takes some time for hydrometeors to reach the earth’s surface. In the comparison of radar rainfall intensities with received signal powers, a delay is often found. The average height of the center of the radar beam for the composites of reflectivities is approximately 1.5 km for the Rotterdam region. The corresponding fall time ranges from 5 to 12 min for terminal fall velocities decreasing from 5 to 2 m s^{-1} . This justifies the selection of the subsequent time step.

3.3. Determination of the Reference Signal Level

[26] The signal attenuation that is ultimately used to derive rainfall intensities is the difference between the received signal level and some reference level that is representative of dry weather. In the second step, this reference signal level P_{ref} is computed for each link and 15 min interval separately by simply taking the median of P for all time steps from the previous 24 h classified as dry, where P is the average of P_{min} and P_{max} . The reference level, and hence the rainfall intensity, is not calculated if the number of dry 15 min periods is less than 10, i.e., 2.5 h in 24 h or 10.4%. Corrected signals P_{min}^C are then introduced on which further analyses are based:

$$P_{\text{min}}^C = \begin{cases} P_{\text{min}} & \text{if wet AND } P_{\text{min}} < P_{\text{ref}}, \\ P_{\text{ref}} & \text{if dry OR } P_{\text{min}} \geq P_{\text{ref}}. \end{cases} \quad (5)$$

Subsequently, the corrected maximum received power is calculated as follows:

$$P_{\text{max}}^C = \begin{cases} P_{\text{max}} & \text{if } P_{\text{min}}^C < P_{\text{ref}} \text{ AND } P_{\text{max}} < P_{\text{ref}}, \\ P_{\text{ref}} & \text{if } P_{\text{min}}^C = P_{\text{ref}} \text{ OR } P_{\text{max}} \geq P_{\text{ref}}. \end{cases} \quad (6)$$

Figure 4 shows for one link that for a wet day (Figure 4, left) the minimum received powers are strongly negatively correlated with the mean path-averaged radar rainfall intensity, as would be expected. The signal fluctuation at 3 UTC is probably not caused by rainfall, as is also the case for the fluctuations during the dry day (Figure 4, right). In general, such undesired signal fluctuations are effectively removed by the proposed link approach, as is also shown in Figure 4 (the blue lines, which represent P_{min}^C).

3.4. Deriving Path-Averaged Rainfall Intensities

[27] The third step is to derive path-averaged rainfall intensities from the corrected minimum and maximum received signal powers with a temporal resolution of 15 min. The temporal sampling strategy and the wet antenna attenuation are taken into account. The rain-induced attenuation is calculated for each time step and link using

$$\begin{aligned} A_{\text{min}} &= P_{\text{ref}} - P_{\text{max}}^C, \\ A_{\text{max}} &= P_{\text{ref}} - P_{\text{min}}^C. \end{aligned} \quad (7)$$

The following model is proposed to calculate the path-averaged mean 15 min rainfall intensity:

$$\begin{aligned} k_{\text{max}} &= \frac{A_{\text{max}} - A_a}{L} H(A_{\text{max}} - A_a), \\ k_{\text{min}} &= \frac{A_{\text{min}} - A_a}{L} H(A_{\text{min}} - A_a), \\ \langle R \rangle &= \alpha a k_{\text{max}}^b + (1 - \alpha) a k_{\text{min}}^b, \end{aligned} \quad (8)$$

where k_{max} and k_{min} are the maximum and minimum specific attenuation (dB km^{-1}), H is the Heaviside function (if the argument of H is smaller than zero, $H = 0$, else $H = 1$), A_a is the attenuation due to wet antennas (dB), assumed independent of rain rate and frequency (in the range used in this study), and α a coefficient that determines the contribution of the minimum and maximum attenuation during a 15 min period.

[28] The assumption of fixed wet antenna attenuation is justified given its relative insensitivity to frequency and its very rapid increase with rain rate to a relatively constant value for rain rates above 4 mm h^{-1} as shown by *Leijnse*

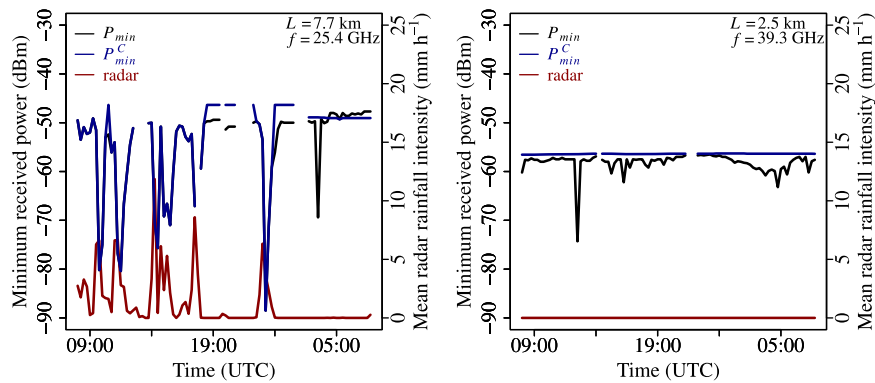


Figure 4. Minimum received powers (black), corrected minimum received powers (blue), and mean gauge-adjusted radar rainfall intensities (red) for (left) a wet day and (right) a dry day.

et al. [2008]. Nevertheless, this approach can result in missed rainfall for weak rain rates. From equation (8), mean 15 min rainfall intensities are calculated for a range of values of α and A_a , which are accumulated to daily rainfall depths (8–8 UTC). The residuals, that is, the differences between the link-based and gauge-adjusted radar-based daily rainfall depths are calculated for each combination of α and A_a . The value of the coefficient α may depend on the link length, and therefore on the link frequency. To account for this possible dependency, the data sets are divided into a low-frequency class of 13–33 GHz and a high-frequency class of 38–39 GHz. Optimal values of α and A_a are selected by searching for the lowest residual standard deviation under

the condition that the mean bias in daily accumulations is smaller than 0.02 mm.

[29] The 2-D contour plots in Figure 5 show that for the CAL 2009 data set the optimal values of α and A_a result in a small bias and a low residual standard deviation. For the link approach these values are $\alpha = 0.334$ and $A_a = 1.30$ dB (low-frequency class, based on 409 residuals), and $\alpha = 0.244$ and $A_a = 1.30$ dB (high-frequency class, based on 515 residuals). The 2-D contour plots for the radar approach are quite similar to those for the link approach. The optimal values of α and A_a become 0.350 and 1.46 dB for the low-frequency class (based on 457 residuals), and 0.240 and 1.18 dB for the high-frequency class (based on

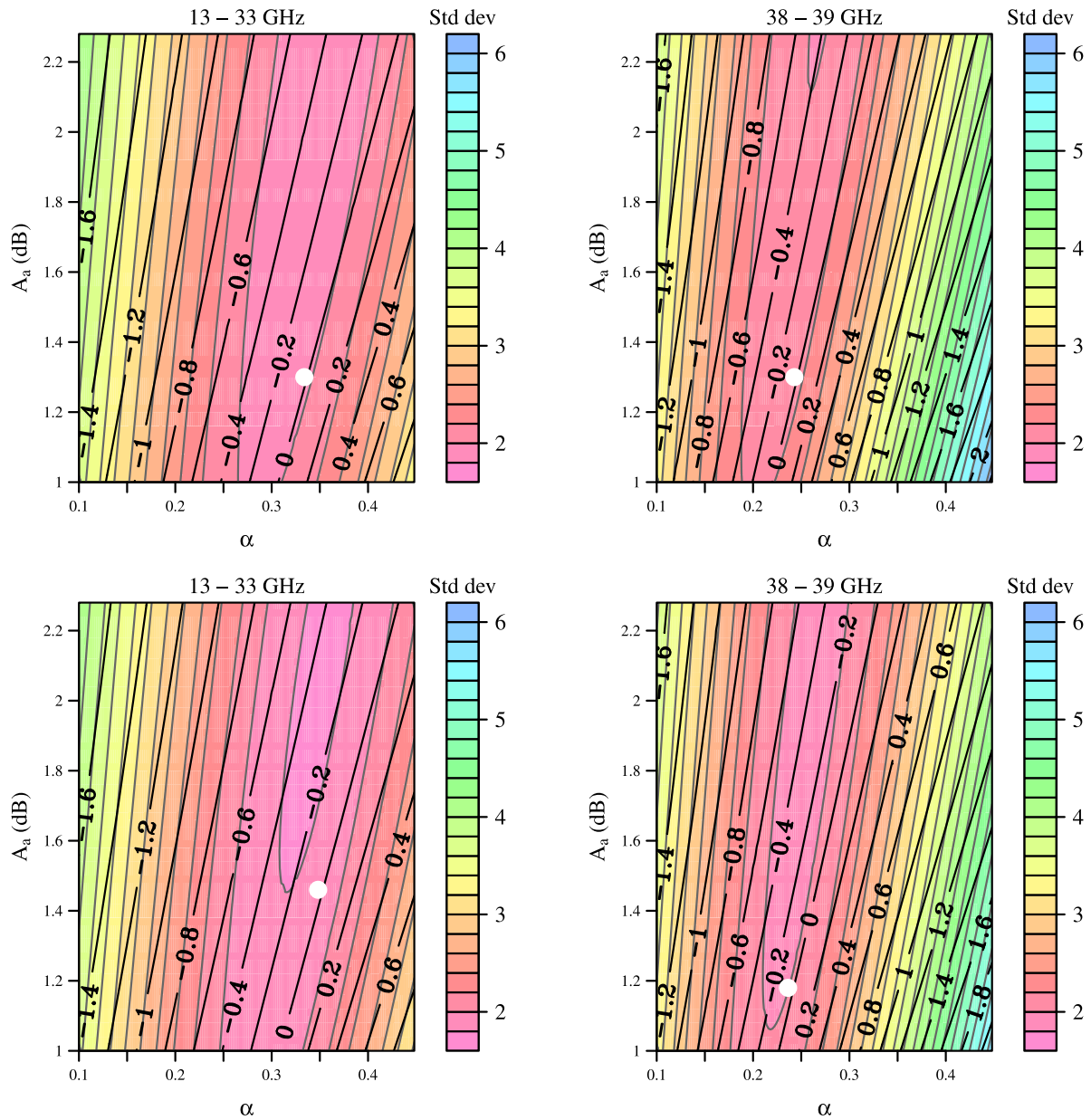


Figure 5. 2-D contour plots for a low- and a high-frequency class showing the residual standard deviation (colors, mm) and the mean bias (black lines, mm) for a combination of values of α and A_a . Figures 5 (top) and 5 (bottom) are based on the link and radar approach to identify wet and dry periods, respectively.

515 residuals). The chosen optimal values for α and A_a are indicated by the white dots in Figure 5.

[30] The same procedure has also been applied to the CAL 2010 data set. For the low-frequency class optimal values of $\alpha = 0.318$ and $A_a = 1.80$ dB (link approach, based on 126 residuals), and $\alpha = 0.276$ and $A_a = 1.32$ dB (radar approach, based on 190 residuals) are found. For the high-frequency class the optimal values are $\alpha = 0.232$ and $A_a = 1.94$ dB (link approach, based on 133 residuals), and $\alpha = 0.246$ and $A_a = 1.82$ dB (radar approach, based on 150 residuals). The values of α are consistently lower for the high-frequency class than for the low-frequency class. The values of α are approximately the same as for the CAL 2009 data set and the values of A_a are larger than those for the CAL 2009 data set, except for the low-frequency class, radar approach.

[31] Using the optimal values for α and A_a (for the specific data set and approach, see Table 3), mean 15 min rainfall intensities are calculated for each link and time step. From these link-based rainfall intensities, 1 h, 3 h, and daily (8–8 UTC) rainfall depths are derived. Figure 6 shows the cumulative rainfall depths from 7 July 2010, 8 UTC to 8 July 2010, 8 UTC for 25 links, representative for the 47 links, for the link approach. The dynamics, i.e., the variation with time, and magnitude of the rainfall depths from radar and links agree reasonably well for many links.

4. Verification and Validation

4.1. Simulation Using Research Link Data

[32] Data from the 27-GHz research link are used to simulate the effect of temporal sampling strategy and the ability of the rainfall retrieval algorithm to cope with this. Mean 15 min rainfall intensities are calculated for a range of values of α using equation (8), where $A_a = 0$ dB since the data have already been corrected for wet antenna attenuation. The mean 15 min rainfall intensities are accumulated to daily rainfall depths. These are compared to the corresponding true mean 15 min rainfall intensity and daily rainfall depths based on 10 Hz link data. By searching for the lowest residual standard deviation provided the bias is smaller than 0.02 mm (day) or 0.02 mm h⁻¹ (15 min), the optimal value of α is found to be 0.331 for daily rainfall depths, being roughly the same as for the commercial microwave links, and 0.332 for 15 min rainfall intensities.

[33] Figure 7 shows that the mean 15 min rainfall intensities and daily rainfall depths are in reasonable agreement

with those based on the 10 Hz link data. This comparison does not suffer from spatial representativeness errors, since the data used to mimic the commercial link are from the same instrument measuring over the same path as the data used to compute the true mean rainfall. This implies that differences can be purely attributed to the ability of the rainfall retrieval algorithm to deal with the temporal sampling strategy. In conclusion, these results are an indication of the robustness of the proposed methodology.

4.2. Daily Link-Based Rainfall Depths

[34] The gauge-adjusted radar data set of daily (8–8 UTC) path-averaged rainfall depths is used to verify the link-based daily rainfall depths. The residuals, that is, the differences between the gauge-adjusted radar rainfall depths and link-based radar rainfall depths, are calculated. A verification against the gauge-adjusted radar daily rainfall depths is given in Figure 8 and Table 4.

[35] Figure 8 shows the scatter plots for the link data, for which the classification of wet and dry spells has been based on the combination of nearby links (link approach, top plot) and unadjusted radar data (radar approach, bottom plot). Results are shown for the CAL 2009 data set (Figures 8a and 8d) and the CAL 2010 data set (Figures 8b and 8e), using the optimized values of α and A_a for these particular data sets. The link-based rainfall depths are in good agreement with the radar rainfall depths for both approaches given the differences in sampling volume. As a result of the optimization procedure, the mean bias is almost zero. The coefficient of variation (CV), which is the residual standard deviation divided by the mean radar rainfall depth (not to be confused with CV_k , the spatial coefficient of variation of the specific attenuation along the link path), is smaller than 1 and the squared Pearson correlation coefficient ρ^2 (i.e., the fraction of the observed variance explained by a linear regression) approximately 0.9 for CAL 2009 and over 0.6 for CAL 2010.

[36] The values of α and A_a may change considerably or equation (8) may be less appropriate for other data sets, for which the temporal variability in rainfall intensity differs. The 2010 data set consists of 21 rainy days, their daily radar rainfall depths being quite large (on average 11.50 mm) compared to the CAL 2009 data set, as is revealed by Figure 8. Section 4.1 shows that different optimal values for α and A_a were found for the CAL 2010 data set.

[37] Using equation (8) and the optimized values of α and A_a from the CAL 2009 data set, daily rainfall depths are calculated for the VAL 2010 data set of commercial microwave links. The CV s and the ρ^2 s are comparable to those of the CAL 2010 data set. A systematic overestimation is found. The mean bias is 33% for the link approach and 19% for the radar approach. The correspondence between the top plots and the bottom plots in Figure 8 confirms that the link approach to identify wet and dry spells is appropriate.

4.3. 1 and 3 h Link-Based Rainfall Depths

[38] The verification of link rainfall depths against gauge-adjusted radar rainfall depths is now extended to subdaily durations. Figure 9 and Table 4 give a verification of 3 h rainfall depths (from 11, 14, 17, 20, 23, 2, 5, and 8 UTC). For the CAL 2009 data set the results for the link approach (Figures 9b and 9e) are similar to those obtained for the radar approach (Figures 9a and 9d). A remarkable

Table 3. Optimal Values of α and A_a for the CAL 2009 and CAL 2010 Data Sets^a

Data Set	α	A_a (dB)
Link (CAL 2009, 13–33 GHz)	0.334	1.30
Link (CAL 2010, 13–33 GHz)	0.318	1.80
Radar (CAL 2009, 13–33 GHz)	0.350	1.46
Radar (CAL 2010, 13–33 GHz)	0.276	1.32
Link (CAL 2009, 38–39 GHz)	0.244	1.30
Link (CAL 2010, 38–39 GHz)	0.232	1.94
Radar (CAL 2009, 38–39 GHz)	0.240	1.18
Radar (CAL 2010, 38–39 GHz)	0.246	1.82

^aValues are given for the link and radar approach to identify wet and dry spells.

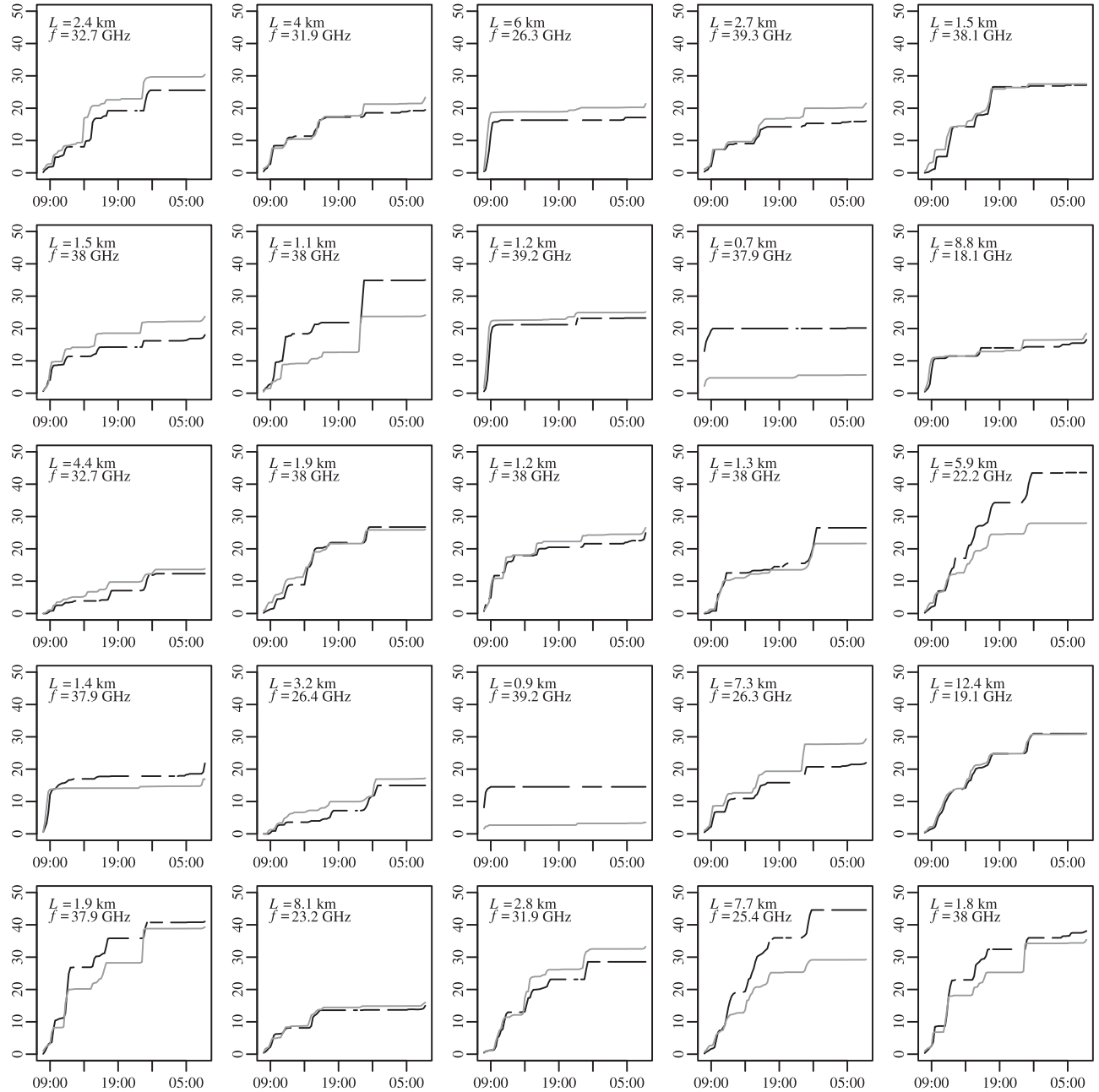


Figure 6. Cumulative rainfall depths in mm (vertical axis) based on gauge-adjusted radar (gray) and link (black) data for 7 July 2010, 8 UTC–8 July 2010, 8 UTC for 25 out of the 47 selected links. Based on the CAL 2009 data set, link approach.

feature concerns the large link rainfall depths for zero radar rainfall depths and vice versa (Figures 9a and 9b). A plausible explanation for this discrepancy is that it takes some time for hydrometeors in the radar beam to reach the earth's surface (section 3.2). At a given time step the radar may already measure rainfall, whereas the link does not yet, or the rainfall has already left the radar beam, while the link still measures rainfall. Similar results are obtained for the 1 h rainfall depths from each hour in Figures 10a and 10b, where the results are only given for the link approach. A large part of this discrepancy disappears when radar rainfall depths of the previous 15 min time interval are used. It also results in a lower CV and a larger ρ^2 .

Advection of precipitation between the cloud base and the ground will partly explain remaining differences.

[39] As for the daily rainfall depths, 1 h and 3 h rainfall depths are also calculated from the VAL 2010 data set of commercial microwave links (link approach). These are shown in Figures 9c, 9f, and 10c. See Table 4 for an overview of the verification results. The 3 h depths moderately correspond with those based on gauge-adjusted radar data, although ρ^2 is above 0.7. Furthermore, the difference between Figures 9c and 9f is less pronounced, suggesting that the fall time of hydrometeors is not that important here. This is probably caused by the relatively high percentage of rainy periods.

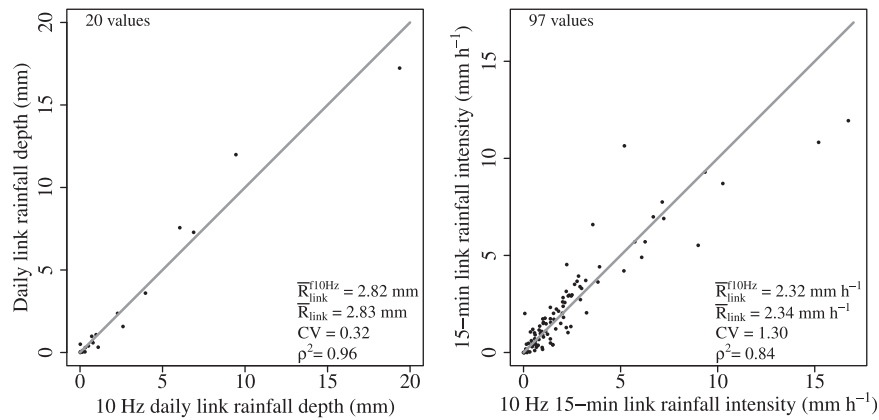


Figure 7. Verification of daily rainfall depths and 15 min rainfall intensities from a research microwave link against those based on its 10 Hz data. The gray line is the $y = x$ line, \bar{R} denotes average rainfall depth along the link, CV is the coefficient of variation, and ρ^2 is the squared Pearson correlation coefficient.

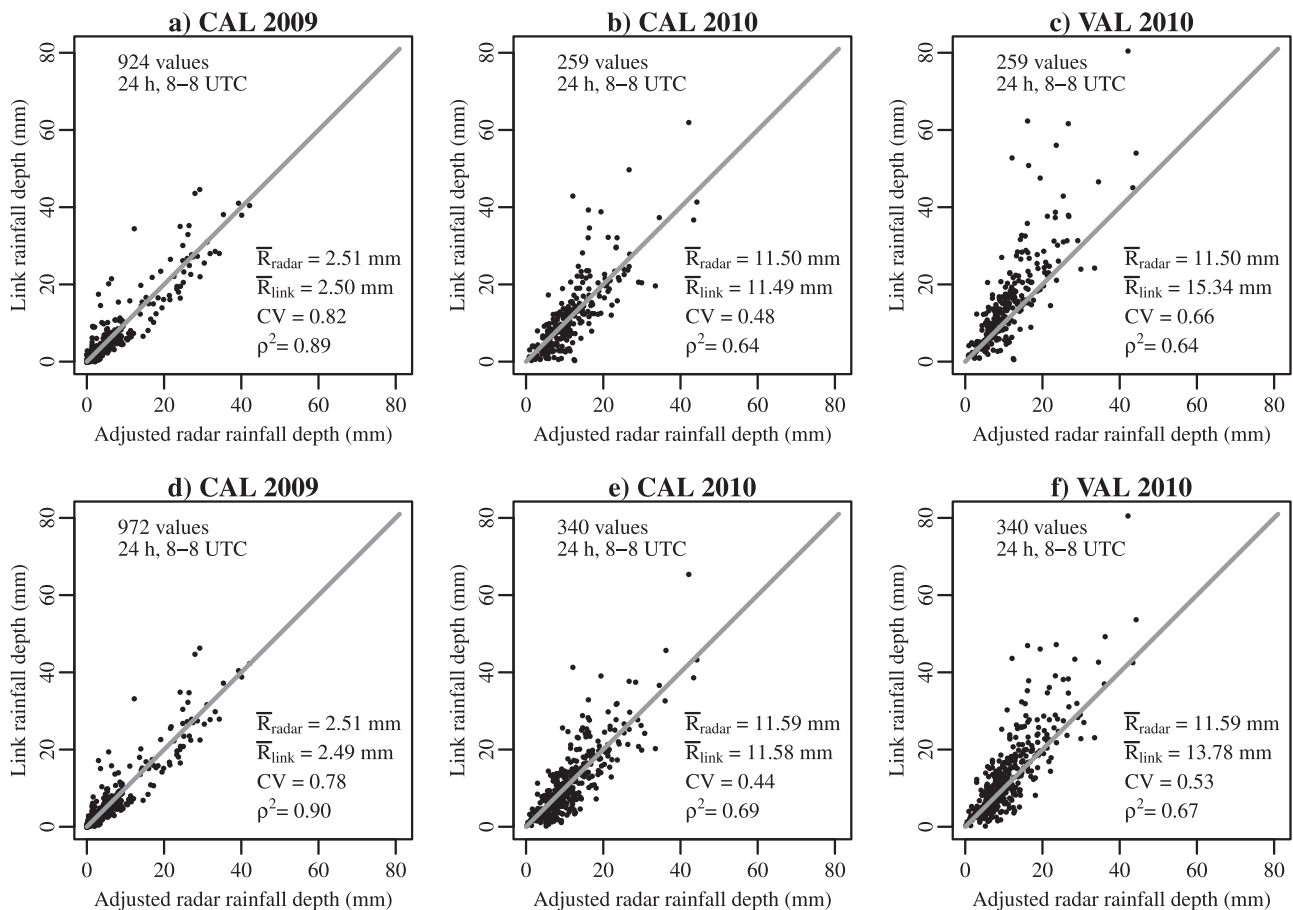


Figure 8. Verification of daily (8–8 UTC) rainfall depths against gauge-adjusted radar rainfall depths for microwave link data. The figures are based on the link (top plots) and radar (bottom plots) approach to identify wet and dry periods. Figures 8c and 8f are a validation. The gray line is the $y = x$ line, \bar{R} denotes rainfall depth along the link, CV is the coefficient of variation, and ρ^2 is the squared Pearson correlation coefficient.

Table 4. Verification of Link-Based Rainfall Accumulations^a

Data Set	Mean Radar (mm)	Bias (%)	CV	ρ^2
24 h, 8–8 UTC:				
Link (CAL 2009)	2.51	−0.7	0.82	0.89
Link (CAL 2010)	11.50	−0.2	0.48	0.64
Link (VAL 2010)	11.50	33.3	0.66	0.64
Radar (CAL 2009)	2.51	−0.8	0.78	0.90
Radar (CAL 2010)	11.59	−0.1	0.44	0.69
Radar (VAL 2010)	11.59	18.9	0.53	0.67
3 h:				
Radar (CAL 2009)	0.31	−0.8	2.63	0.68
Link (CAL 2009)	0.31	−0.7	2.71	0.67
Link (VAL 2010)	1.44	33.3	1.30	0.71
3 h (−15 min):				
Radar (CAL 2009)	0.31	0.3	1.95	0.82
Link (CAL 2009)	0.31	0.4	2.05	0.80
Link (VAL 2010)	1.44	33.1	1.28	0.73
1 h:				
Link (CAL 2009)	0.10	−0.7	4.94	0.50
1 h (−15 min):				
Link (CAL 2009)	0.10	0.4	3.26	0.76
Link (VAL 2010)	0.48	33.1	1.78	0.68

^aResults are shown for the link and radar approach to identify wet and dry spells, and for the calibration (CAL) and validation (VAL) data set. Mean radar-based rainfall depths, bias in the mean rainfall, coefficient of variation (CV), and squared Pearson correlation coefficient (ρ^2) for the verification and validation with the gauge-adjusted radar data.

4.4. Areal Rainfall Depths

[40] Areal daily link-based rainfall depths are calculated for the VAL 2010 data set (radar approach) to verify whether accurate regional rainfall over the Rotterdam urban area can be estimated from the link data. For each day separately, the areal average is calculated as the mean rainfall depth over all links, based on link data ($\bar{R}_{\text{link}}^{1-D}$) and radar data ($\bar{R}_{\text{radar}}^{1-D}$), and based on all radar pixels within a radius of 20 km from Rotterdam, the regional radar rainfall depth ($\bar{R}_{\text{radar}}^{2-D}$). Figure 11 shows a verification of the mean link rainfall depth against the mean radar rainfall depth along the links (Figure 11a) and the regional radar rainfall depth (Figure 11b). Figure 11c shows that the differences between the mean radar rainfall depths along the links and the regional radar rainfall depths are small. Hence the link locations are representative for estimating the regional rainfall depth and the differences between the mean link rainfall depths and the regional radar rainfall depths (Figure 11b) are largely caused by differences between mean link and radar rainfall depths at the same location (Figure 11a). Despite the positive bias of 22% in link-based areal rainfall depths, the high values of ρ^2 and low values of CV show that useful regional rainfall estimates can be derived from mean link data. For the link approach (not shown) the bias becomes rather large (53%). Comparison of 1 h mean link rainfall depths with regional radar rainfall depths (VAL 2010, radar approach, not shown), reveals a bias of 22%, a larger CV (1.38) and a lower ρ^2 (0.73).

5. Discussion

5.1. Link Approach

[41] The developed link approach, in which a mutual decrease in minimum received powers of nearby links is employed to identify wet spells, works well on the 2009 as

well as the 2010 data set. Daily and 3 h rainfall depths have a similar performance as those based on the radar approach, where radar data are used to distinguish between wet and dry spells. The link approach leads to practically no reduction (5%) in the average number of selected links for the CAL 2009 data set with respect to the radar approach. Only for the VAL 2010 data set, which has a relatively low link density, a 24%-reduction in the average number of selected links does occur (in parentheses, Table 2) compared to the radar approach. Therefore, the suitability of the link approach is limited to dense link networks with a high data availability. On average 6 (VAL 2010) to 12 (CAL 2009) nearby links were used in the link approach. The ΔP_L criterion (Appendix B) is less important in correctly identifying wet and dry periods, which is expected because the design of the network. Some errors that occur in the link data sets during dry weather may also occur during rainy periods. This is not specifically dealt with, only indirectly in the calibration. Finally, nearby links may suffer simultaneously from signal fluctuations not caused by rainfall, resulting in a poor performance of the link approach. Results show that this does not occur often.

5.2. Reference Signal Level and Rainfall Retrieval Algorithm

[42] The reference signal level is determined as the median of received signal level data from dry weather conditions for each 15 min period and link separately. The choice for the median is based on its insensitivity to outliers as compared to the mean received signal level. After a rain event it may take some time for the antennas to become dry. This may have some influence on the value of the reference level. Furthermore, the wet antenna attenuation depends somewhat on the rainfall intensity and the rainfall duration [Leijnse *et al.*, 2008], whereas a fixed value is assumed in this study. Note that this value is optimized for each frequency class. Finally, the fact that it may rain only between and not on the antennas, or that it may rain on just one antenna, is not taken into account.

[43] A_a is presented as the wet antenna attenuation, but may also compensate for other sources of error. For instance, it may indirectly contain a reference signal level correction. The value of A_a of approximately 1.2–1.9 dB is relatively small, which indicates that the commercial microwave links are relatively insensitive to wet antenna attenuation (compared to, e.g., 3.32 dB by Leijnse *et al.* [2007a]). The value of A_a may also be partially influenced by the chosen value of α .

[44] The values of α of approximately 0.24 for the high-frequency class or 0.34 for the low-frequency class (both CAL 2009 data set) imply that the maximum rainfall intensity is assigned a lower weight than the minimum rainfall intensity. This is an indication of an asymmetrical temporal probability distribution of the path-averaged rainfall intensity over 15 min, with a positive skewness. Note that the minimum rainfall intensity is probably often close to zero, which will also be of influence. The larger value of α for the low-frequency class is probably related to the longer link lengths, which are less prone to the influence of local temporal variations in rainfall intensity.

[45] Mixed-phase hydrometeors at ground level hardly occur in Netherlands during April to August. Most

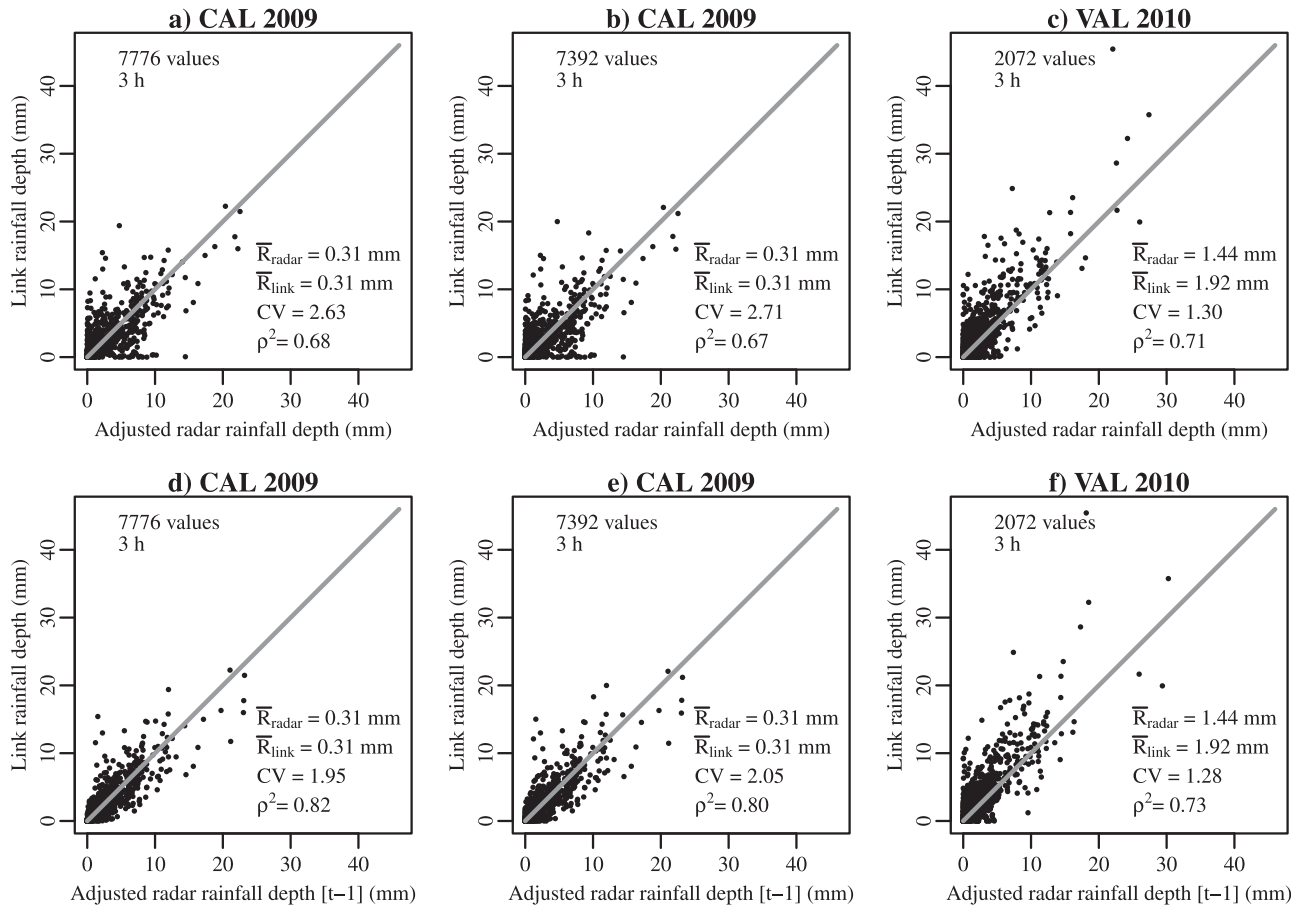


Figure 9. Verification of 3 h microwave link rainfall depths against gauge-adjusted radar rainfall depths for (b, c, e, and f) the link approach and (a and d) the radar approach to identify wet and dry periods. In Figures 9d–9f the 3 h radar rainfall depths of the previous time step (-15 min) have been used. Figures 9c and 9f represent validations. The gray line is the $y = x$ line, \bar{R} denotes average rainfall depth along the link, CV is the coefficient of variation, and ρ^2 is the squared Pearson correlation coefficient.

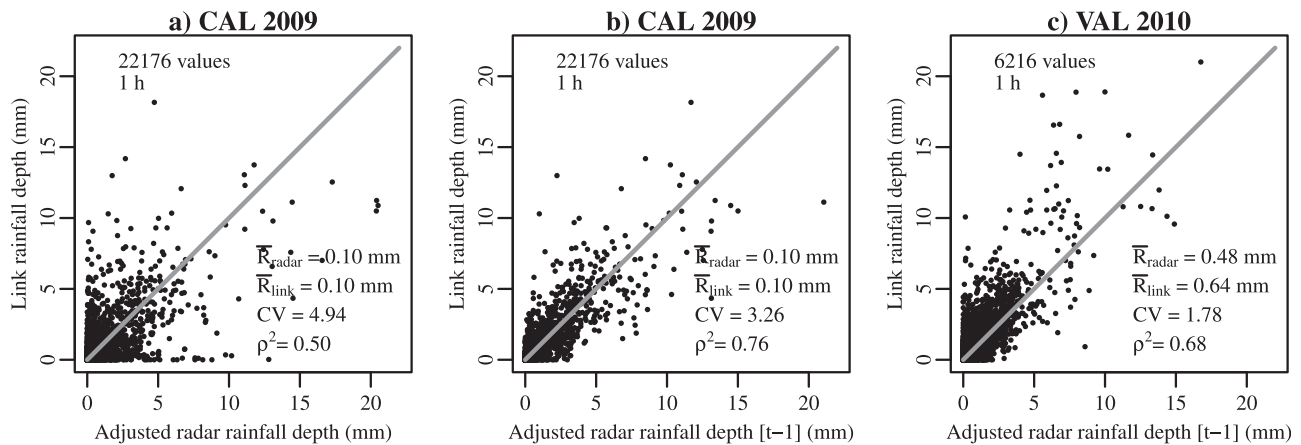


Figure 10. Verification of 1 h microwave link rainfall depths against gauge-adjusted radar rainfall depths for the link approach to identify wet and dry periods. Figure 10c represents a validation. In Figures 10b and 10c the 1 h radar rainfall depths of the previous time step (-15 min) have been used. The gray line is the $y = x$ line, \bar{R} denotes average rainfall depth along the link, CV is the coefficient of variation and ρ^2 is the squared Pearson correlation coefficient.

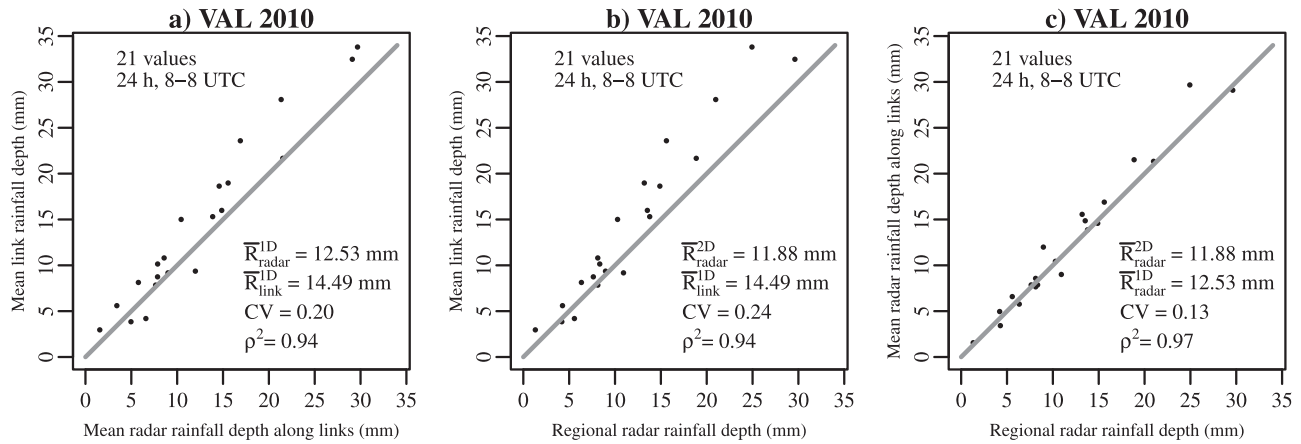


Figure 11. Comparison of areal daily rainfall depths. Verification of mean link rainfall depth ($\bar{R}_{\text{link}}^{1-D}$) against (a) mean radar rainfall depth ($\bar{R}_{\text{radar}}^{1-D}$) along the links and (b) the regional radar rainfall depth within a radius of 20 km from Rotterdam ($\bar{R}_{\text{radar}}^{2-D}$). (c) Verification of mean radar rainfall depth against regional radar rainfall depth. The gray line is the $y = x$ line, CV is the coefficient of variation, and ρ^2 is the squared Pearson correlation coefficient.

instantaneous hourly air temperatures at 1.5 m height from Rotterdam airport, located 3.9 km from the Rotterdam city center, are above 5 and 10°C for the 2010 and 2009 data set, respectively. Moreover, *de Haij* [2007] shows that solid or freezing precipitation constitutes on average only 7% of the total time of precipitation in the Netherlands. Its effect on the water budget will even be less. This was based on many years of human and automatic observations in eight locations. The largest part will be caused by winter precipitation, showing that the percentage of freezing or solid precipitation in the observation periods in this study, April to August, will be negligible. Note that the developed retrieval algorithm is only applicable to rainfall estimation. In general, commercial microwave link networks are not suitable for measurement of solid precipitation.

5.3. Verification

[46] The verification of link-based rainfall depths is not entirely independent for the CAL 2009 and 2010 data sets, since the gauge-adjusted radar rainfall data have been used in the selection of threshold values and the calibration of α and A_a . However, α and A_a are estimated only for each frequency class using 17 or 21 days of data. In addition, only three threshold values have been estimated for the classification of wet and dry periods utilizing the CAL 2009 data set only. The verification shows that the dynamics, i.e., the variation with time, and magnitude of the rainfall depths from radar and links agree reasonably well for many links.

[47] The quality of link-based rainfall depths is confirmed independently using a commercial microwave link validation data set of 21 rainy days (VAL 2010). The results are promising, although a bias of 19% (radar approach) and 33% (link approach) is found in the daily rainfall depths. This can be mainly attributed to the different rainfall types (convective/stratiform) of the VAL 2010 data set as compared to the CAL 2009 data set. The selection of the validation data has been conducted without any prior knowledge about their quality.

[48] The availability of link data is 91% for the CAL 2009 data set, whereas the availability of radar data is close to 100%. Note that daily accumulations based on link data were computed even if some data (up to 16.7% or 4 h) are missing. If rain was present in these periods, this will hence cause an underestimation of the accumulation. The optimal values of α and A_a , which have been estimated using the radar data, may compensate for missed rain by the link. This could give rise to overestimation in the validation using the VAL 2010 data set, for which the availability of link data is 98%.

5.4. Differences Between Link and Radar Rainfall Depths

[49] It is more appropriate to compare the link-based rainfall depths with the radar-based ones from the previous time step (–15 min) for durations of 1 and 3 h. This is probably caused by the fall time of hydrometeors between the radar beam (center at 1.5 km height) and the earth's surface. Differences in timing are also related to the fact that the available commercial link data are the minimum and maximum received powers over 15 min periods.

[50] The gauge-adjusted radar data are averaged over the length of the link and, since little rain gauge data are available, are an important tool in the verification and validation. Part of the differences between link-based and radar-based rainfall depths can be attributed to differences in sampling volume, the five-pixel median filter, and advection of rainfall between the radar beam and the ground. The gauge-adjusted radar rainfall depths are assumed to be the ground truth. The sampling time interval of 5 min and remaining errors in the radar data, such as attenuation or changes in the vertical profile of reflectivity, can reduce the quality of the radar data, particularly for short durations. Specifically, the radar will often measure in or above the melting layer. The combination of a daily spatial adjustment and an hourly mean-field bias adjustment is expected to remove much of the resulting biases and removes part of these errors on subdaily time scales [Overeem et al., 2009a, 2009b].

5.5. Link Length and Frequency

[51] The residuals were normalized with their daily rainfall depths and plotted against their corresponding link frequency (not shown), which revealed that their magnitude does not depend on link frequency. Only links with a length larger than 0.7 km were considered. Often, unrealistically large rainfall depths were found for shorter links. This could for instance be caused by the relatively large value of A_a with respect to the rain-induced attenuation.

6. Conclusions and Recommendations

[52] Commercial microwave link data sets were used to derive quantitative precipitation estimates for the Rotterdam region, a large, densely populated urban area in Netherlands. A link approach was developed to identify wet and dry spells using the received signal levels from nearby links. Subsequently, rainfall intensities were calculated from the corrected received signal levels taking into account temporal sampling strategy and wet antenna attenuation. Link-based rainfall depths were compared against gauge-adjusted radar rainfall depths.

[53] Long data sets of commercial microwave links for Netherlands have been used to estimate rainfall depths. This study confirms that commercial microwave links are useful for quantitative precipitation estimation in urban areas. The proposed rainfall retrieval algorithm is computationally inexpensive and relatively simple, and is meant as a first step toward operational use of commercial microwave link data over the entire land surface area of Netherlands. Furthermore, the characteristics of commercial microwave links used worldwide are quite similar. Because of this, these links hold a promise for measuring rainfall in areas where few or no weather radars or rain gauges are available. Finally, they may also serve as a potentially new source of rainfall information for adjustment of radar data, assimilation in numerical weather prediction models, or ground validation of satellite-based rainfall estimates.

[54] The selection of appropriate threshold values to identify wet and dry spells, based on the CAL 2009 data set only, needs to be investigated for larger data sets containing many different rainfall types. It is promising that these threshold values also work quite well for the 2010 data set.

[55] The contribution of the minimum and maximum attenuation was assumed constant for each frequency class. However, the value of α is expected to be dependent on the type of rainfall. Nevertheless, the validation already shows the potential of this approach using the VAL 2010 data set, which has different rainfall properties. The verification using a research link, of which characteristics differ from the commercial links, also gives an indication of the robustness of the proposed rainfall retrieval algorithm to deal with temporal sampling strategy. Nevertheless, the selection of appropriate values for α and A_a needs to be investigated more thoroughly for larger data sets in time and space. Particularly, the distribution of rainfall within the 15 min interval is of interest here and the value of the wet antenna attenuation. This can be investigated experimentally with a research link, preferably of the same type as the commercial links. This may also lead to a more complicated rainfall retrieval algorithm.

[56] Attention needs also to be given to the further development of methods to obtain high-quality rainfall maps from the link-based path measurements of rainfall.

Appendix A: Taylor Series Expansion of Point Scale R - k Relation

[57] This appendix shows that the R - k relation at the point scale $R(k) = ak^b$ provides a good approximation for the path-averaged rainfall intensity $\langle R \rangle$ as well. A second order Taylor series expansion of $R(k)$ is developed around $\langle k \rangle$ to obtain a better approximation to the relationship between $\langle R \rangle$ and $\langle k \rangle$ [Leijnse et al., 2010a; Uijlenhoet et al., 2011]:

$$R(k) = R(\langle k \rangle) + (k - \langle k \rangle)R'(\langle k \rangle) + \frac{1}{2}(k - \langle k \rangle)^2 R''(\langle k \rangle) + \dots, \quad (\text{A1})$$

where $R'(\langle k \rangle)$ is the first order and $R''(\langle k \rangle)$ the second order derivative of $R(k)$ with respect to k , evaluated at $k = \langle k \rangle$. Equation (A1) can be approximated by

$$R(k) \approx a\langle k \rangle^b + (k - \langle k \rangle)ab\langle k \rangle^{b-1} + \frac{1}{2}(k - \langle k \rangle)^2 ab(b-1)\langle k \rangle^{b-2}. \quad (\text{A2})$$

Taking averages (expectations) on both sides gives

$$\begin{aligned} \langle R \rangle &\approx a\langle k \rangle^b + \frac{1}{2}\text{var}(k)ab(b-1)\langle k \rangle^{b-2} \\ &= \left[1 + \frac{1}{2}b(b-1)\frac{\text{var}(k)}{\langle k \rangle^2} \right] a\langle k \rangle^b, \end{aligned} \quad (\text{A3})$$

where $\text{var}(k)$ is the variance of k along the link. This can be written as

$$\langle R \rangle \approx \left[1 + \frac{1}{2}b(b-1)CV_k^2 \right] a\langle k \rangle^b. \quad (\text{A4})$$

This equation shows that the path-averaged rainfall intensity also depends on CV_k , the coefficient of variation (ratio of standard deviation and mean) of the specific attenuation along the link. The spatial variability of k , and hence that of rainfall, is of influence. Particularly in convective rainfall, CV_k can be considerable. Because the spatial variation of R cannot be derived from the received power, CV_k cannot be calculated. Nevertheless, because the value of the exponent b is close to 1 (Figure 3, left), equation (4) still gives a good approximation of $\langle R \rangle$. This is confirmed by Figure 3 (right), where the error due to neglecting the CV_k term in equation (A4) is given for different frequencies and values of CV_k . A slight overestimation is found for the lowest frequency, 13 GHz, and some underestimation for the highest frequency, 39 GHz.

Appendix B: Classification of Wet and Dry Spells Using the Link Approach

[58] The link network in the Netherlands is relatively dense. Hence the focus of this study is on estimating

rainfall from this link network and the focus is not on using every available single link, for which the link approach is not applicable. A step-by-step description of the classification algorithm goes as follows:

- [59] 1. Select a single link for a 24 h period (8–8 UTC).
- [60] 2. Select all links for which both ends are within 10 km from either end of the already selected link.
- [61] 3. Continue if at least two surrounding links have been selected, otherwise the link is not used. In that case go to step 1 and select another link.
- [62] 4. Calculate $\Delta P = P_{\min} - \max(P_{\min})$ and $\Delta P_L = \frac{P_{\min} - \max(P_{\min})}{L}$ for each link and each 15 min period. For each 15 min period $\max(P_{\min})$ is calculated as the maximum value of P_{\min} over the previous 24 h for the considered link.
- [63] 5. For each 15 min period calculate the median values of ΔP and ΔP_L over all selected links.
- [64] 6. If $\text{median}(\Delta P_L) < -0.7 \text{ dB km}^{-1}$ and $\text{median}(\Delta P) < -1.4 \text{ dB}$ the 15 min period is classified as wet.
- [65] 7. If for a given 15-min period that is classified as wet $\max(P_{\min}) - P_{\min} > 2 \text{ dB}$ the previous 30 min and the next 15 min are classified as wet.
- [66] 8. All 15 min periods that have not been classified as wet are classified as dry.
- [67] 9. Repeat these steps for all other links and every available 24 h period (8–8 UTC).
- [68] The threshold values in steps 6 and 7 have been optimized by visual comparison with the gauge-adjusted radar data set of path-averaged rainfall intensities employing the CAL 2009 data set only. It should be noted that this classification is only based on the minimum received signal level. Schleiss and Berne [2010] propose a wet/dry classification algorithm based on data with a very high temporal sampling (up to a few milliseconds). This could not be applied here, since such information was not available for this study and will hardly ever be available for commercial microwave link networks.
- [69] Note that Berne *et al.* [2004] find that the range of the variogram, which describes the decorrelation distance, is larger than 15 km for a time interval of 15 min for typical intense Mediterranean rain events. In the Netherlands this range is expected to be longer, because rainfall is on average less intense and less convective compared to the Mediterranean. This justifies selecting all links for which both ends are within 10 km from either end of the already selected link in the link approach.
- [70] The link approach can fail in case the surrounding links do not encounter rain but the link for which rain has to be estimated does. This will not occur that often since the spatial extent of rainfall in a 15 min interval will frequently exceed 15 km. Furthermore, the average link length is 3.7 km and the links are usually not oriented parallel to each other. This increases the probability that surrounding links also encounter rain.

[71] **Acknowledgments.** We gratefully acknowledge Ronald Kloeg and Ralph Koppelaar from T-Mobile NL for providing the cellular telecommunication link data and answering our questions about the data. The authors acknowledge the comments given by Artem Zinevich, Kevin Paulson, and one anonymous reviewer, which motivated us to improve our paper.

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